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HSD-TR-88-001

NOISE AND SONIC BOOM IMPACT TECHNOLOGY

BOOMAP2 Computer Program for Sonic Boom Research: Technical Report

Volume I of III Volumes

AD-A198 892

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August 1988

Final Report for Period July 1986 - November 1987

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Noise and Sonic Boom Impact Technology Program
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UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY: N/A	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): Report 6487, NSBIT TASK ORDER 0001	5. MONITORING ORGANIZATION REPORT NUMBER(S): HSD-TR-88-001, Vol. 1
6a. NAME OF PERFORMING ORGANIZATION: BBN Laboratories Incorporated; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: HSD/YA-NSBIT
6c. ADDRESS (City, State and ZIP Code): 21120 Vanowen Street, Canoga Park, CA 91303	7b. ADDRESS (City, State and ZIP Code): Wright-Patterson AFB, Ohio 45433-6573
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Noise & Sonic Boom Impact Tech.; 8b. OFFICE SYMBOL (If applicable): HSD/YA-NSBIT	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F33615-86-C-0530
8c. ADDRESS (City, State and ZIP Code): Wright-Patterson AFB, Ohio 45433-6573	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
63723F	3037	02	01

11. TITLE (Include Security Classification) (U)BOOMAP2 Computer Prog. for Sonic Boom Research:Vol.1,Tech.Rpt

12. PERSONAL AUTHOR(S) Bishop, Dwight E.; Haber, Jerold M.; Wilby, Emma G.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final	FROM 7/86 TO 11/87	June, 1988	

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	
20	01		sonic booms
12	05		modelling

19. ABSTRACT (Continue on reverse if necessary and identify by block number) Air Combat Maneuvering Instrumentation/Tactical Air Combat Training Systems (ACMI/TACTS) are used at several Military Operating Areas (MOA) in the United States and abroad as a post-flight pilot debriefing aid in training for air-to-air combat. Engineering flight data are acquired and recorded from several radar facilities simultaneously during flights in appropriately instrumented MOAs. These data are used to generate the information required for subsequent graphical replays of the aircraft position, airspeed, g-value, attitude, climb/dive angle, etc., of the the training sortie at post-flight debriefings. The BOOMAP2 and MOAOPS computer programs analyze noise from supersonic aircraft operations by extracting information from the ACMI/TACTS computer tapes. The MOAOPS program extracts information from a TACTS/ACMI mission standard data tape and compiles a computer library of information concerning the supersonic operations. The BOOMAP 2 program utilizes the library produced by the MOAOPS program. The program calculates various statistics on the supersonic operations, and calculates expected sonic boom levels on the ground based on the extracted information. BOOMAP2 can: (1)generate various spatial

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Geral L. Long, Lt. Col., USAF	(513) 255-8416	HSD/YA-NSBIT

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19. (continued)

/temporal distribution statistics; (2) interface with sonic boom generation and propagation models; (3) calculate the intensity and location of sonic booms reaching the ground; and (4) provide the data file used by a commercial graphical software package, GRCP, to plot contours of boom exposure in units of average peak overpressure or C-weighted day-night average sound level (CDNL).

These two programs, when used with an adequate library of aircraft sorties from Military Operating Areas, can be an invaluable tool for environmental planning purposes to predict boom intensity, frequency, and distribution.

This report describes the technical basis for the BOOMAP2 program developed under this contract. The BOOMAP2 program utilizes a sophisticated acoustic ray theory model for predicting the sonic boom overpressures and noise levels on the ground. The model is a modified version of the TRAPS computer program earlier developed by Dr. Albion Taylor. This BOOMAP2 program replaces the earlier BOOM-MAP program which could not provide accurate predictions of the booms resulting from non-steady supersonic aircraft flight.

Keywords: ... computer models; noise pollution; (KT)

PREFACE

The BOOMAP2 computer program is the result of effort by several individuals. In particular, the authors of the technical report wish to acknowledge the volunteer technical assistance of Dr. Albion Taylor, author of the TRAPS program, for his help in locating program errors and in developing useful corrections. The actual computer programming was undertaken by Phil Day, Tom Reilly, and Harry Seidman of XonTech.

The support and encouragement of the NSBIT Technical Staff is also gratefully acknowledged as is the continuing support by Mr. Jerry D. Speakman of the Biodynamics and Bioengineering Division, Aerospace Medical Research Laboratory, Wright-Patterson AFB.

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$A(t)$ = age at time t along the ray

$A'(x_1)$ = area distribution of slender body

C = pressure coefficient

F = F-function for aircraft signatures

F_A = area component of F-function

F_B = lift component of F-function

F_{A1}, F_{B1} = nondimensionalized area and lift contributions

F_f = F-function conversion factor

F_i = input F-function

J = Jacobian, used to define raytube area

K_s = aircraft shape factor

K_l = aircraft life parameter

L_F = a length used to nondimensionalize the F-function

L_ce = C-weighted sound exposure level (CSEW, dB)

L_pk = maximum flat-weighted sound pressure level, dB

M = aircraft Mach number

O = aircraft heading

P = atmospheric pressure

P_A = atmospheric pressure at the aircraft

$p(\phi,\psi)$ = pressure far field signature

R = relative radius of curvature

S distance from the caustic along the ray

$S'(x_1,\phi)$ = area distribution of equivalent body of resolution

V = aircraft speed

V_A = average velocity vector

W = aircraft weight

X* = distance to focal zone boundary, tangential to the focus

Y = distance normal to the focus

Y* = distance to focal zone boundary, normal to the focus

c = local speed of sound at a given altitude

c_A = speed of sound at aircraft

l = aircraft characteristic length, typically fuselage tough (Section 4)

n_L = lift load factor

Subscript

A = aircraft

o = initial value at time of emission of a ray from aircraft

n_x, n_y,

n_z = unit normal components in x, y, and z directions

(p,q,r) = vector components of normals to phase surfaces of wave numbers (relative to airborne reference frame)

pu = atmospheric pressure at aircraft altitude (Section 4)

q = $.5 P_A \gamma M_y^2$ = dynamic pressure

r = distance from aircraft flight path

r = aircraft speed at time t

t = time along ray

u,v = wind components at a given altitude

x_1 = coordinate system near aircraft aligned with ray

x,y,z = ground coordinate system (east, north, and height above sea level, respectively)

$x(t_A)$, $y(t_A)$, $z(t_A)$ = aircraft location at time t_A

Γ = $(\gamma + 1)/2$

Φ = local perturbation velocity potential function

β = $\sqrt{M^2-1}$

γ = ratio of specific heats for air

Δ = airspeed component in horizontal plane

Δp = peak overpressure

Δo = aircraft airspeed

Δp = perturbation pressure, incremental pressure to the sonic boom

Δs = incremental change in ray location = 800 ft

$\Delta u \; \Delta v$ = velocity difference of wind components at aircraft altitude

$\vec{\kappa}_c$ = caustic curvature vector

$\vec{\kappa}_R$ = ray curvature vector

$\vec{\kappa}_{rel}$ = relative curvature vector between ray and caustic surface

μ = Mach cone angle, $\sin^{-1}(\;)$

ξ = position behind the nose

Subscript

A = aircraft

o = initial value at time of emission of a ray from aircraft

ρ	=	atmospheric density
ϕ	=	azimuth angle of ray from vertical plane or ray bank angle
ϕ inc	=	incremental ray bank angle per unit distance
ψ	=	phase (identified with position)
ω	=	frequency (scaled by A/C length) equal to the airspeed in the airborne reference frame

Subscript

A = aircraft

o = initial value at time of emission of a ray from aircraft

BOOMAP2 COMPUTER PROGRAM FOR SONIC BOOM RESEARCH: VOLUME 1. TECHNICAL REPORT

1.0 INTRODUCTION

The BOOMAP2 and MOAOPS computer programs are utilized to analyze noise from supersonic aircraft operations in Military Operating Areas (MOA's). The two programs are designed to extract and analyze information from the Tactical Air Crew Combat Training System/Air Combat Maneuvering Intrumentation (TACTS/ACMI) manufactured by the Cubic Corporation. The TACTS/ACMI system digitizes various positional and performance parameters of the aircraft in a Military Operating Area at frequent intervals for later replay in graphic or tabular form during air crew briefings.

The MOAOPS program (Ref. 1) extracts information from a TACTS/ACMI mission standard data tape and compiles a computer library of information concerning the supersonic operations. The BOOMAP2 program utilizes the library produced by the MOAOPS program. The program calculates various statistics on the supersonic operations. It also calculates expected sonic boom levels on the ground based on the extracted information. Both programs are written in FORTRAN 77 and operate in batch mode on Control Data Corporation (CDC) CYBER 170 Series machines.

The BOOMAP2 program is capable of predicting the noise levels or overpressures on the ground resulting from either carpet or focus sonic booms resulting from air combat maneuvering training flights. The output of the program consists of:

(a) Various statistical summaries.

(b) Flight track information.

(c) A computer library of predicted overpressures on the ground for each flight analyzed.

(d) "Scratch pad" plots showing maximum overpressures when focused sonic booms occur.

(e) Calculated noise levels at a grid of ground positions (100 x 100 matrix).

The output of the BOOMMAP2 program is designed to be compatible with GPCP (General Purpose Contouring Program) (Ref. 2). Through the use of the GPCP program, the BOOMAP2 output can be displayed in terms of: (a) a map showing the flight track segments where the aircraft was supersonic; (b) displays of the calculated sonic boom "noise" in terms of several metrics; and (c) a map showing the location of focused sonic booms.

The BOOMAP2 computer model utilizes a sophisticated acoustic ray theory model for predicting the overpressures and noise levels on the ground, which is based upon the TRAPS program developed by Dr. Albion Taylor (Ref. 3). The version of the TRAPS program in BOOMAP2 incorporates several corrections and changes over the original program. The BOOMAP2 program also incorporates several additions to the original TRAPS program to permit estimation of overpressures at focus locations.

The BOOMAP2 program replaces the BOOMMAP program developed earlier (Ref. 1). The major difference betwee programs is that the original BOOMMAP program utilized calculation procedures for estimating booms based on the simplified sonic boom prediction model methods developed by Henry Carlson (Ref. 4). These calculations assumed steady state flight and were not intended to provide accurate predictions for focus booms. The current program provides much more accurate calculation of overpressures at and near focus.

This report is one of three documents describing the BOOMAP2 program. The other documents consist of a user's guide (Ref. 5) and a maintenance manual (Ref. 6).

Section 2 of this report presents an overview of both BOOMAP2 and the MOAOPS programs. Section 3 provides a more complete technical description of the sonic boom propagation code incorporated in BOOMAP2. Section 4 describes the aircraft F-functions incorporated in the program. Section 5 summarizes the rationale for the selection of the TRAPS program as a basis for model calculations. Results from this program are compared to those from other ray tracing programs and field measurements in Section 6. Section 7 provides recommendations for future study. Appendix A provides some examples of program output.

2.0 PROGRAM OVERVIEW

The major purpose of the BOOMAP2 and the accompanying MOAOPS program is to extract and analyze information from the Tactical Air Crew Combat Training System/Air Combat Maneuvering Instrumentation (TACTS/ACMI) system installed at various combat training military operating areas in order to predict the location and magnitude of sonic boom overpressures on the ground in the vicinity of supersonic flights.*

Real time flight information is transmitted to the TACTS/ACMI systems on ground. Among the data is real time information on aircraft position, velocity and acceleration, updated at intervals of 100 to 200 milliseconds. The MOAOPS program extracts this data for the sonic boom analysis from the tapes at approximately 1.5 second intervals in order to minimize both the time taken to read the tapes and the quantity of information to be stored.

The MOAOPS program is in two parts: a data extraction program EXTRCT, and an index deletion and modification program DELETE. The data extraction program reads the ACMI tapes, extracting relevant information and appending this information to either a new or existing data base (library). The library file accumulates the information from all the mission tapes analyzed. This library file is indexed so that a particular mission, aircraft type, etc. can be accessed by the sonic boom analysis programs.

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* In this report, overpressure will typically mean the "magnitude" of the sonic boom at a given point expressed in terms of the maximum overpressure in pounds per square foot (psf) or in terms of the overall sound pressure level (OASPL) in dB, or in terms of the C-weighted sound exposure level (CSEL) in dB. Program options allow a choice of either of these three metrics for the contour presentations.

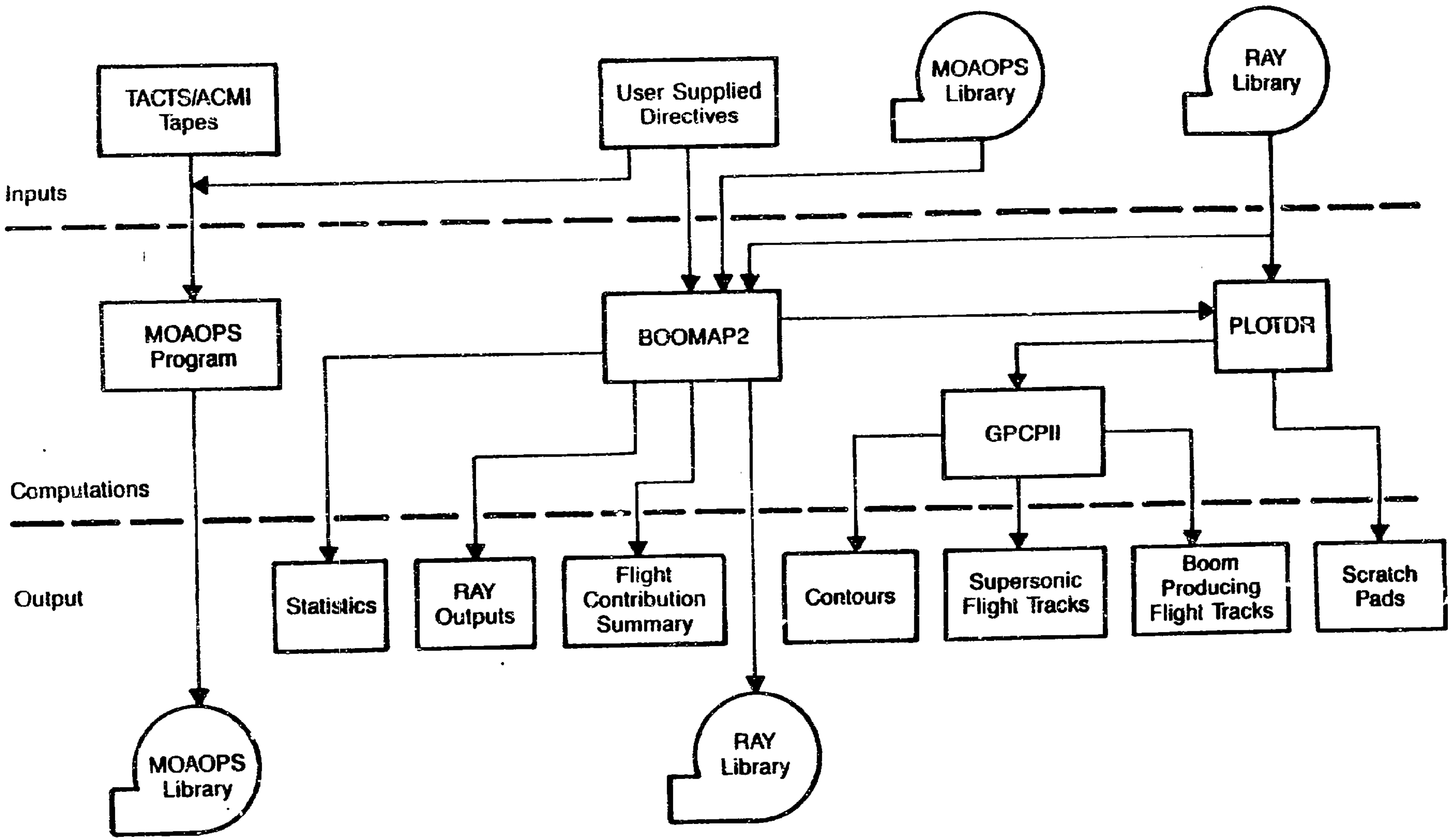

Figure 1. Functional Relationship Between Elements of BOOMAP2 Computer Program

The BOOMAP2 data analysis program accesses the MOAOPS library tapes as selected by the user. The data analysis program produces statistical and graphical output describing the aircraft positions parameters as various measures of predicted boom strength. The BOOMAP2 program produces tabular output of various statistics that is sent directly to a line printer. The overpressures predicted on the ground by the acoustic ray theory model are output to the printer and also stored as a computer library for future access. In addition, for those situations where focused sonic booms are produced, individual plots of the maximum overpressures together with other technical information are produced in form of a "scratch pad". These "scratch pads" can be plotted for each situation in which focused booms occur.

When a mission is selected from the MOAOPS library and used as a BOOMAP2 computer program, the rays traced by BOOMAP2 are saved in a RAYS library. If that same mission is selected at a future time, the necessary ray information is recalled from the library, thereby saving substantial computer time.

To produce graphic output, BOOMAP2 creates a file which is compatible with California Computer Products (CALCOMP) General Purpose Contouring Program (GPCP-II). GPCP-II reads this file and generates the necessary plotter directors to produce hard copy graphic output.

The user controls the data base subset to be extracted from the MOAOPS library through the use of an input data file. Through this file, the user specifies: a) the name(s) of the MOA ranges to be considered; b) mission names or dates; c) bounding times of day; and d) aircraft types (specific tail numbers optional).

Users also specify the desired output products. These include:

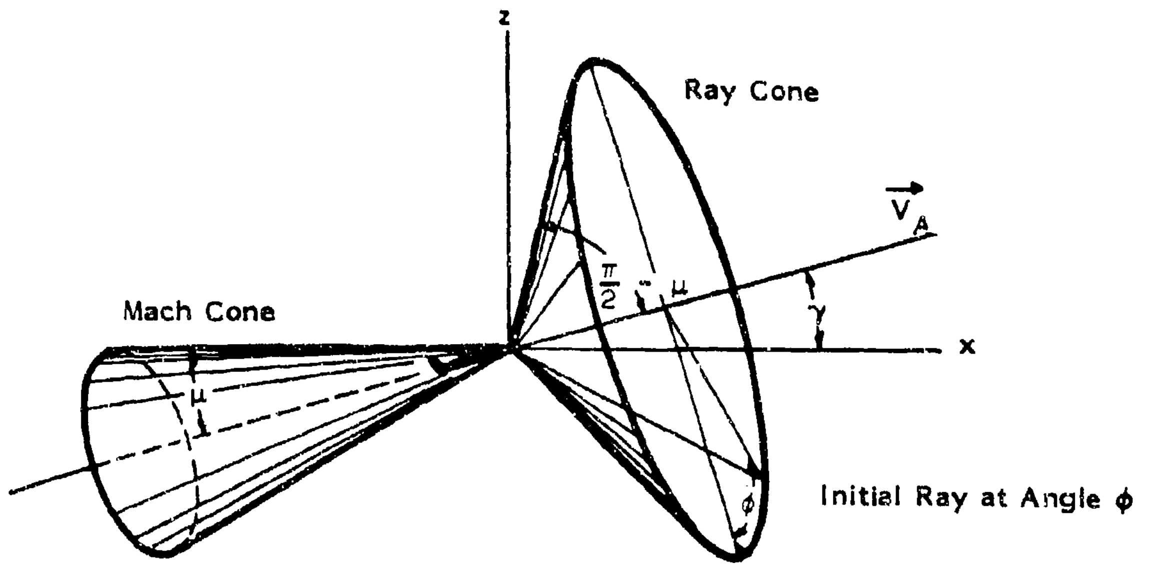

FIGURE 2. THE MACH CONE AND RAY CONE.

1. A statistical summary of position, speed, and boom strength variables. This summary includes distribution functions of range x-coordinates and y-coordinates, and the aircraft z-coordinate (height above the range), all in feet. It also includes a distribution function of effective height (h_e). Distribution functions of Mach number, cutoff Mach number, and effective Mach number are also presented. Estimated boom strength distribution functions include peak overpressure (in pounds per square foot), the peak overpressure (in dB, re: 20 microPascals), the C-weighted sound exposure level (in dB), and the A-weighted sound exposure level (in dB). Also included are root mean square values for effective height, Mach number, effective Mach number, and cutoff Mach number.

2. A flight track map depicting ground projections of flight paths during supersonic activity.

3. A flight track map depicting ground projections of flight paths during sonic boom producing activity.

4. A noise contour map of average C-weighted sound exposure levels (CSEL).

5. A noise contour map of C-weighted day-night average levels (CLDN). This requires input of the reference number of daytime operations which is used to convert CSEL to CLDN.

6. A noise contour map of average peak overpressures in pounds per square foot, or OASPL.

7. A map showing the geographic location of maximum overpressures due to focused sonic booms.

Examples of the BOOMAP2 program output are shown in Appendix A.

3.0 TECHNICAL OVERVIEW OF THE SONIC BOOM PROPAGATION CODE

This report provides a technical overview of the sonic boom propagation code incorporated in BOOMAP2. The code is based upon the TRAPS program developed by Dr. Albion Taylor (Ref. 3).* Modifications to the code consisted of

a) eliminating some programming errors that were discovered in the course of the project;

b) augmenting the program with a technique for estimating the sonic boom signatures at a simple focus using a similitude developed by Gill and Seebass (Ref. 7) and originally implemented by Plotkin (Ref. 8). Portions of the code from the FOBOOM program developed by Dr. Kenneth Plotkin have been used;

c) constraining the propagation to consider only the portion of the sonic boom wave front originating beneath an aircraft and the propagation through a standard still (no wind) atmosphere;

d) developing a driver for selection of the portion of the sonic boom footprint to be traced and ground signatures to be saved.

A body moving through the atmosphere at supersonic speeds will continuously generate a system of shock waves in its wake. Under appropriate atmospheric conditions these sonic boom shock waves will produce a disturbance at the ground. Computer programs for estimating the ground level sonic boom must include the following elements:

- A method for generating (describing) a trajectory for the supersonic craft

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* Much of this section is adopted directly from Ref. 3.

- A method for characterizing the system of shock waves generated about the craft

- A description of those atmospheric parameters that affect the propagation of the sonic boom shock waves

- A method for characterizing the path of the shock wave propagation through the atmosphere

- A method for evaluating the effect of the atmosphere on the magnitude and shape of the sonic boom waves

- A method for accounting for the reflection/attenuation of the sonic boom at the ground

- A technique for assembling and presenting the results in a meaningful fashion

3.1 The Aircraft Flight Path

Both the original TRAPS program and BOOMAP2 use recorded flight path information to characterize the supersonic aircraft trajectories. In TRAPS, the displacements of the aircraft are used to fit a cubic spline from which the acceleration vectors are calculated. These are smoothed and an inverse spline is used to calculate the smoothed aircraft locations.

BOOMAP2 uses a standard cubic spline fit of the velocities to calculate the acceleration vectors. The accelerations are smoothed and quadratic coefficients are calculated using a weighted linear least squares method which are then used to interpret the aircraft flight data at any specific time between the input aircraft track times.

The flight path information serves three functions in the sonic boom propagation analysis:

1. It provides an initial location from which the sonic boom shock wave is propagated. At each time point along the flight path the sonic boom shock wave system originates at the leading edge of the aircraft; other aircraft features generate the detail of the waveform at the location of these features. The length of the aircraft (and hence, the initial length of the system of shock waves) is much shorter than the distance from the aircraft to the ground. Thus, the path of the shock wave system may be characterized by tracing the path of the leading shock.

2. The leading shock wave (near the aircraft) will be a conical wave (called the Mach one) with the axis of symmetry along the aircraft velocity vector, $\vec{V}_A$ (Figure 2). The aircraft Mach number, M ($M = |\vec{V}_A| / c_A$, c_A is the speed of sound at the aircraft), is related to the apex half-angle, μ , by $1/M = \sin$. The initial direction of propagation of the wave is at ninety degrees to the surface of the Mach cone; the collection of the initial directions of propagation forms a cone called the ray cone. Thus, the aircraft velocity vector determines the initial direction of propagation of the shock wave.

3. The ray cones generated by an aircraft accelerating along its velocity vector will have progressively larger apex angles (Figure 3). Thus, corresponding portions of the wave front generated at short time intervals from each other will tend to constructively interfere with each other at some distance from the aircraft. (The distance from the aircraft at which this occurs will depend on the rate of acceleration and the manner in which the atmosphere modifies the propagation path from a

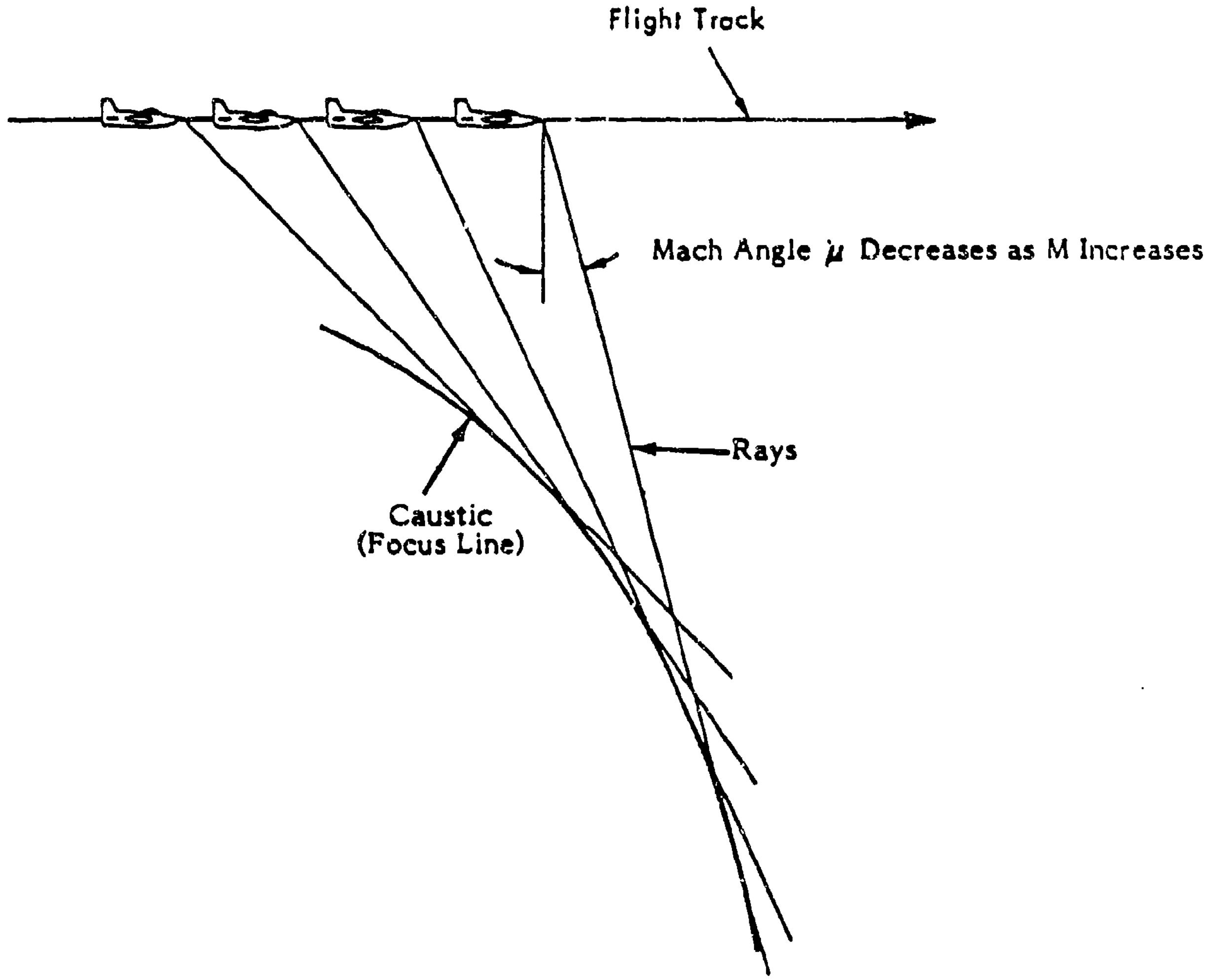


FIGURE 3. SONIC BOOM FOCUS DUE TO ACCELERATION.

straight line.) Analogously, an aircraft engaged in a constant speed turn will, over successive time periods, generate ray cones whose axes are misaligned (Figure 4). The misalignment of the ray cone axes causes the ray cones to be closer to each other on one side of the cone and further from each other on the opposite side of the cone. This effect is maximal in the plane of the turn. On the side in which the ray cones are tilted toward each other there is an intensification of the signal, while on the opposite side the sonic boom levels are diminished. Since all maneuvers can be described as combinations of these basic maneuvers, the effect of a maneuver will be some local intensification (rarification) of the sonic boom. The magnitude of the aircraft acceleration and jerk will affect the location of this enhanced (subdued) sonic boom and the degree of amplification or diminishment.

3.2 The Near Field Signature

In order to extrapolate the sonic boom overpressure signatures to the ground, a sonic boom propagation code must be provided a description of the disturbance of the atmosphere generated by the supersonic aircraft. This disturbance may be described as an overpressure waveform that an observer near the aircraft would measure as the aircraft flies by, or equivalently, in terms of a theoretically derived F-function, defining the flow near the aircraft. Both the TRAPS program and BOOMAP2 computer program use this latter approach.

This approach develops the initial acoustic signal from the aircraft geometry and its lift distribution which are used to develop a velocity perturbation potential function. (A velocity potential is a function whose gradient describes the velocity induced in the fluid.) After a number of simplifications, the potential function can be expressed in terms of an "equivalent

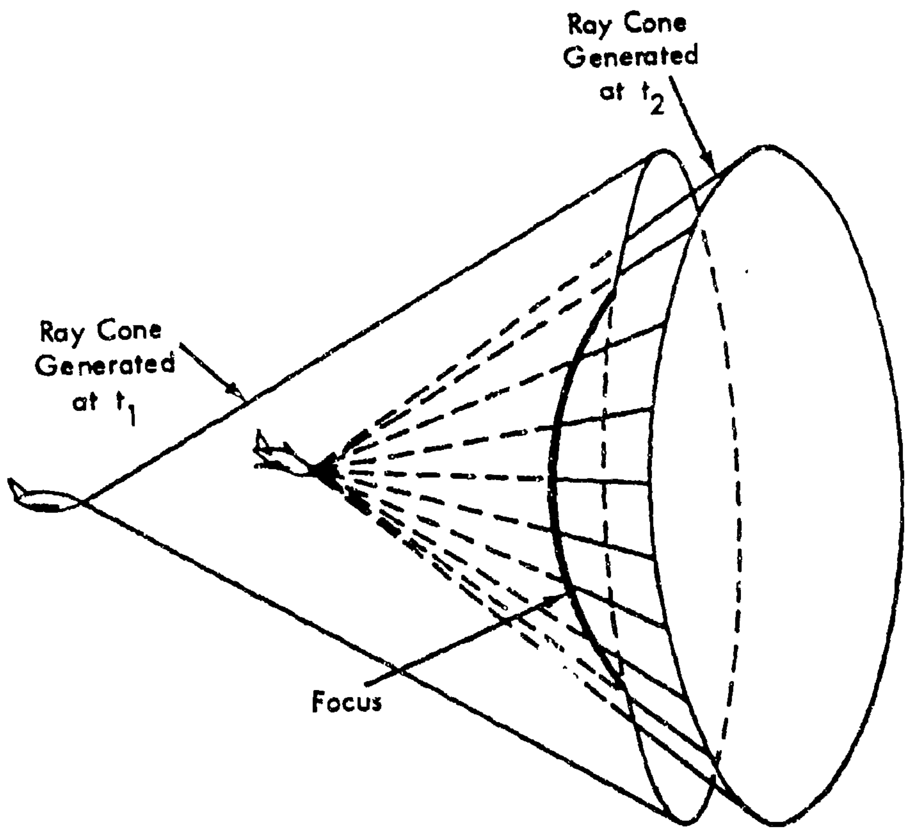


FIGURE 4. TURN FOCUS: THREE DIMENSIONS.

area" distribution $S'(x_1, \phi)$. The equivalent area distribution is the sum of two terms. The first is the derivative, $A'(x_1)$, taken in the direction of the aircraft velocity vector of the aircraft cross-sectional area cut by a plane oriented at the Mach angle, μ.

The second is given by $\frac{\beta}{\rho V^2} \ell(x_1)$ where

$\beta = \sqrt{M^2-1}$

ρ = atmospheric density

V = aircraft speed

$\ell(x_1)$ = the rate of change in the x_1 direction of the components of the combined effect of the lift and the side forces in the negative ϕ direction.

The resulting asymptotic expression for the potential function is

$$\Phi(x-\beta r, r, \phi) = \frac{-1}{2\pi \sqrt{2\beta r}} \int_{-\infty}^{x-\beta r} \frac{S'(x_1)\,dx_1}{\sqrt{x-\beta r-x_1}}$$

where r is the distance from the aircraft flight path. The perturbation pressure, p, is given by $-\rho V^2{}_x$. On differentiating the potential function this gives

$$-\Phi_x = \frac{\Delta p}{\rho M^2 c_A^2} = \frac{1}{\sqrt{2\beta r}} F_i(x-\beta r, \phi)$$

where

$$F_i(x-\beta r, \phi) = \frac{1}{2\pi} \int_{-\infty}^{x-\beta r} \frac{S''(x_1, \phi)\; dx_1}{\sqrt{x-\beta r-x_1}}$$

Alternatively, the relationship for the perturbation pressure may be written in the form

$$\frac{\Delta p}{\rho c_A^2} = \frac{F}{\sqrt{r}}$$

where

$$F = F_i \; F_f$$

$$F_f = \frac{M^2}{\sqrt{2\beta}}$$

This F-function can be further decomposed into area and lift components F_A and F_B as follows

$$F = F_f(F_A + F_B \cos\ )$$

$$F_A = F_{A1}(L_F)^{\frac{1}{2}}$$

$$F_B = F_{B1} \frac{.5\ \beta\ (n_L W/_q)}{(L_F)^{3/2}}$$

where n_L = lift load factor

W = aircraft weight

q = $0.5 P_A \gamma\, M^2$ = dynamic pressure

P_A = atmospheric pressure at the aircraft

γ = ratio of specific heats for air

L_F = a length used to nondimensionalize the F-function

= Nondimensionalized area and lift contributions.

Note that an unnormalized F-function, F_A, may be related to a measured nearfield signature close to the aircraft by the relationship

$$\Delta p = \frac{\gamma P_A M^2}{\sqrt{2r\beta}} F_A$$

The TRAPS program input consists of the component F-functions F_{A1} and F_{B1}. In BOOMAP2, the TRAPS code to handle the component F-functions has been retained intact, but is presently unused. The BOOMAP2 code employs simplified F-functions based upon a procedure developed by Carlson (Ref. 4). The development of the simplified F-function is described in Section 4 of this report.

3.3 The Atmospheric Description

While the propagation of sonic boom through the atmosphere is affected by the detailed characterization of the atmosphere (temperature, pressure, winds, and chemical composition), as a practical matter useful results may be obtained by employing simplified descriptions. A common approach used is to describe these atmospheric properties as being horizontally stratified and temporally constant. This has the practical consequences of making the propagation analysis significantly more tractable and creating mathematical models consistent with the meteorological data available to use with them while sacrificing only the ability to model what are normally rather localized effects (focusing or attenuating sonic boom waveforms by small scale anomalies). This omission is likely to be important only for those atmospheric variations in the immediate vicinity of either the aircraft or the ground.

The TRAPS program was designed to employ a combination of a built-in 1976 standard atmosphere; pressure, temperature, and dewpoint data profiles obtained from rawinsondes or rocketsondes and a wind profile obtained from similar sources. The BOOMAP2 code differs only in that the ability to process wind data or nonstandard atmosphere has not been verified. The meteorological parameters play three major roles in the models adopted: a) specification of the atmospheric pressure at the source and key altitudes, b) defining the "effective speed of sound" in the direction of propagation as a function of altitude, and c) defining the

effective speed of sound gradient seen by the advancing shock wave. The consequences of these are to displace the sonic boom footprint, affect the amplitude of the initial disturbance and to determine the extent of attenuation/enhancement of the shock wave by the atmosphere.

3.4 Propagation

The sonic boom propagation is based upon the theory of geometric acoustics with selected modifications to address its peculiar characteristics. The theory of geometric acoustics is valid when the wave length is small compared with characteristic macroscopic scales of the problem. Such scales include the radii of curvature of the wave fronts and the scale heights of the atmosphere. Geometric acoustics is invalid near the aircraft, near a focus, and near the boundary of and within a shadow zone. In these areas alternative models are required.

Standard acoustic theories are linear. For sonic boom propagation, the cumulative effect of non-linear effects over large distances are significant. The cumulative non-linear effects distort the signal and produce shock waves.

The basic concept of the geometric theory is the propagation of the sonic boom along rays, trajectories of points on the wave front. Because the wavelength is substantially smaller than the characteristic macroscopic scales of the problem, it suffices to trace only the rays originating from the leading edge of the shock wave. In addition, the analysis is based on the assumption that the cumulative non-linear effects do not affect the ray geometry. This is an accepted assumption for most sonic boom problems of interest including characterization of a focal region.

An additionally important concept for the analysis is that of ray tube. A ray tube may be visualized as a collection of rays

emitted from the aircraft initially displaced from each other by small times or distances. It is useful to define a quantity which provides a measure of the energy density since it is related to the amplitude of the signal. Such a quantity is the ray tube area (to be defined more precisely later).

As a consequence of the foregoing assumptions and the horizontally stratified atmosphere, ray tracing may be performed using a form of Snell's law. Using this approach, ray-tube areas may be calculated employing a straightforward numerical integration. The amplitude of the signal and the amount of signal distortion may then be derived as a function of these quantities.

3.5 Reflection at the Ground

The measured magnitude of a weak shock wave normally incident to a perfect reflector will be twice the free field overpressures. As a consequence of energy absorption by the ground, the observed reflection factors are typically slightly less than two. As the angle of the incidence to the ground becomes more oblique, the reflection factor decreases, approaching one at cutoff (the location at which raypaths have been refracted to the horizontal direction at the earth's surface).

Although geometric acoustics would predict no sonic boom in the shadow zone beyond cutoff, as a consequence of diffraction effects, a low frequency rumble will be heard in this zone. A third phenomenon that occurs near the cutoff boundary is the focusing of the rays which are turning up. As a consequence, observed reflection factors have the greatest spread near cutoff.

The BOOMAP2 program models the reflection factor of 2.0 for the entire sonic boom carpet out to 80 percent of the cutoff distance. At cutoff, levels are reduced by 10 dB over those relative with a reflection factor of 2. Beyond cutoff, the

levels are assumed to decrease at a rate of 25 dB per decade distance until a level of 80 dB CSEL is reached. Calculations for a ray are then terminated. This procedure allows rapid truncation of the boom levels beyond cutoff, but avoids major discontinuities in noise level changes with distance.

3.6 Ray Tracing

The program assumes the atmosphere (pressures, temperature, and winds) to be stratified in the vertical direction, but uniform in the horizontal direction and steady in time. These assumptions impose stringent conditions on the possible paths of motion (rays) of the wave. This motion is governed by a variant of Snell's law, which by virtue of the stratification of the atmosphere, requires the horizontal components of wave number, the frequency, and hence the horizontal velocity of the phase surfaces of the wave to be constant with respect to the ground. This constant differs from one ray to another. When combined with the requirement that the net speed be that of sound relative to the air, it determines the size of the vertical component of motion, and thus, the motion itself. The result is that, for each ray, there are combinations of wind velocity and temperature at which it cannot exist. Where the ray can exist, its path curves toward regions more favorable to it; i.e., toward levels where the sound speed is lower and/or where the wind component in its direction is greater (Figure 5). For each ray there is a critical combination of temperature and wind velocity that will cause its vertical motion to slow, stop, and reverse (acoustical cutoff).

It should be noted that a downward moving ray which meets such a reversal layer and turns away from the ground will never, because of the stratification assumptions, reach the ground no matter what path it subsequently follows, but will always reverse again at the same height.

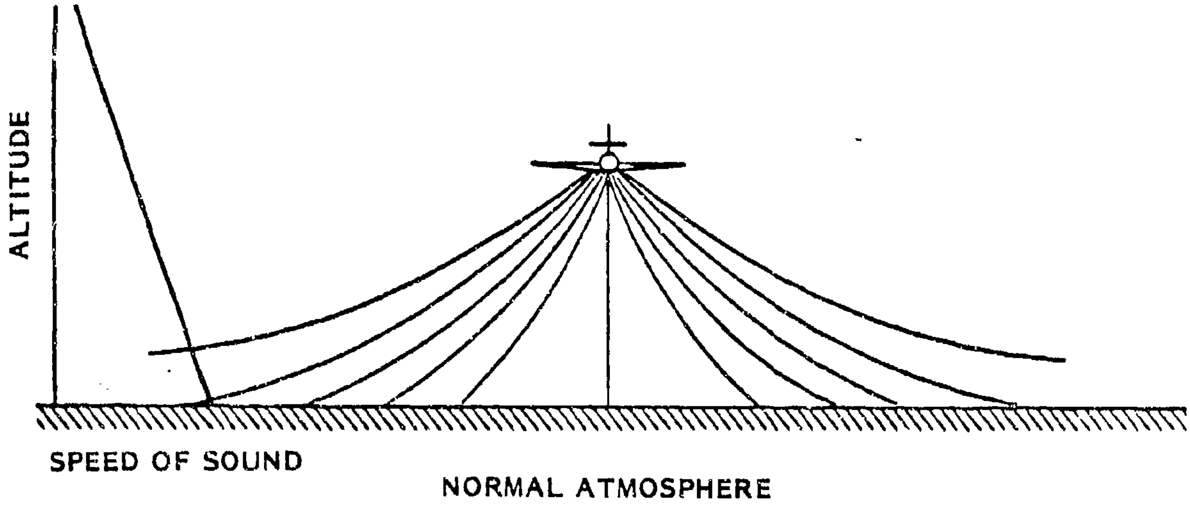


FIGURE 5. RAY CURVATURE IN A STANDARD ATMOSPHERE WITH NO WINDS--HEAD-ON VIEW.

In a reference frame at rest in the air at the altitude of the aircraft (airborne reference frame), the normals to the phase surfaces of the wave can be taken to have vector components (p, q, r) in the X-, Y-, and vertical (Z-) directions, respectively. These components represent the wave numbers in their respective directions; the magnitude of this vector times the sound speed is the frequency (scaled by the aircraft length), which in the airborne reference system is taken as equal to the airspeed of the aircraft.

The tips of these vectors in the airborne system must lie on a sphere whose radius is the aircraft Mach number. In addition, it can be shown that the component of the vector in the direction of the aircraft trajectory must be unity. This means that the tips of the vectors must lie in the intersection of the Mach-number radius sphere with a plane normal to the aircraft motion; i.e., on a circle which is called the Mach circle (Figure 6). The cone (ray cone) formed by the vectors from the origin to the Mach circle represents all the possible ray directions (in the airborne reference system) from the aircraft at any instant; its apex half-angle, whose cosine is the inverse of the Mach number, is the co-Mach angle. An individual ray in the cone is specified by an angle, , which is measured along the Mach circle from the lowermost ray, clockwise as seen by the aircraft pilot (Figure 2).

In transferring from the airborne reference frame to one fixed at the ground, the wave numbers p, q, and r do not change. The frequency ω, changes according to the rule

$$\Delta\omega = \Delta up + \Delta \; vq$$

where u and v denote the components of the velocity difference between the two frames (i.e., the wind components at aircraft altitude).

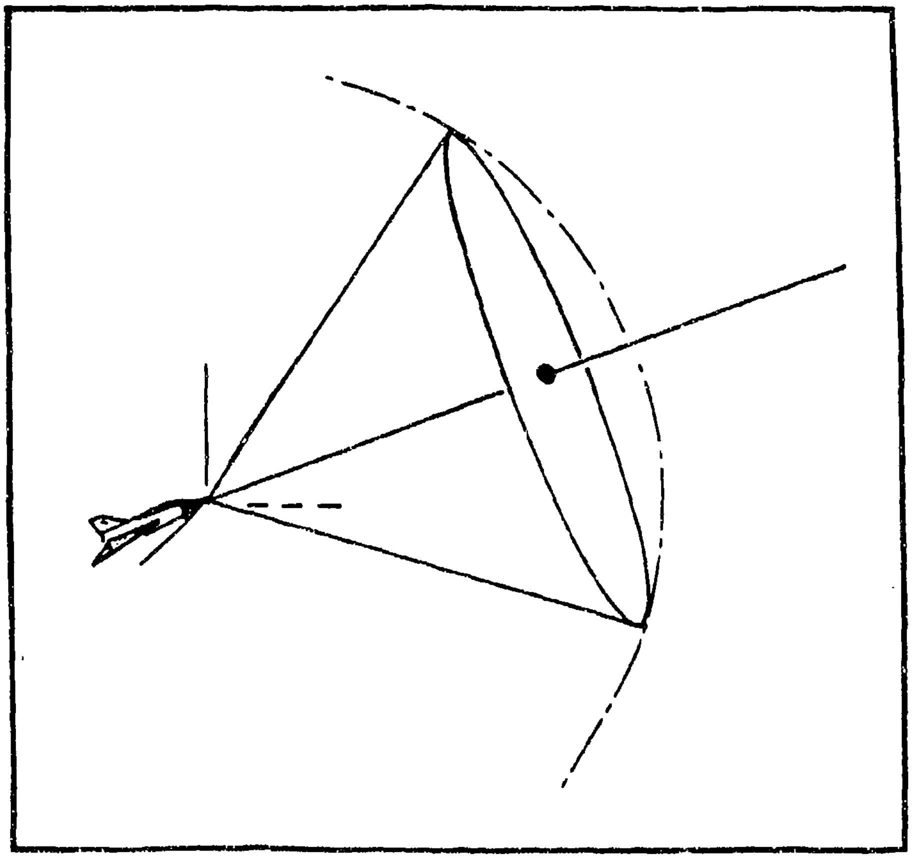


FIGURE 6. THE MACH SPHERE, THE MACH CIRCLE, AND THE RAY CONE.

Because of the stratification assumptions, it may be shown that in any unaccelerated reference frame, the parameters , p, and q do not change as the wave propagates along a ray. This is the acoustic version of Snell's law. In addition, the following relation, known as the Eiconal equation, holds:

$$c^2(p^2 + q^2 + r^2) = (\omega + up + vq)^2$$

at any altitude, where u, v, and c are the wind components and the speed of sound, respectively, at that altitude. This defines an admittance region in the form of an ellipse for initial conditions which can reach the ground. In general, the admittance ellipse intersects the projection of the Mach circle at four points, splitting the Mach circle into four arcs, two lying inside the admittance ellipse and two outside. The arcs within the admittance region correspond to rays which can penetrate to the ground; those without cannot. One of the two admitted arcs will consist predominantly, or exclusively, of rays in the upper part of the Mach circle (i.e., rising rays), the other of the rays in the lower part (descending rays).

The program contains a routine to carry out the construction of the admittance ellipse at ground level, and to determine for which initial orientations, ϕ, the rays will lie inside the ellipse. Since interest is in the sonic boom on the ground, the program declines to trace rays outside the admittance ellipse which saves computer time and printout.

For a ray within the admittance ellipse initial conditions for ray tracing are determined as follows. The initial position of the ray is taken at the tip of the aircraft $(x(t_A), y(t_A), z(t_A))$ with the initial direction of propagation given by the ray bank angle, ϕ , the aircraft Mach number, M, the aircraft heading, θ , and climb angle, γ (both relative to the wind). The

initial wave numbers and frequency are then calculated as

$$\Delta_o = M\, c_A$$

$$p_o = -\frac{\Delta_o}{c_A}[\sin(\mu)\ \sin(\theta)\ \cos(\gamma) + \cos(\mu)\ \sin(\phi)\ \cos(\theta) - \cos(\mu)\ \cos(\phi)\ \sin(\theta)\ \sin(\gamma)]$$

$$q_o = -\frac{\Delta_o}{c_A}[\sin(\mu)\ \cos(\theta)\ \cos(\gamma) - \cos(\mu)\ \sin(\phi)\ \sin(\theta) - \cos(\mu)\ \cos(\phi)\ \cos(\theta)\ \sin(\gamma)]$$

$$r_o = -\frac{\Delta_o}{c_A}[\sin(\mu)\ \sin(\gamma) + \cos(\mu)\ \cos(\phi)\ \cos(\gamma)]$$

$$\omega_o = \Delta_o - u_o p_o - v_o q_o - w_o r_o.$$

The following equations are then used for the ray tracing calculations:

$$\dot{x} = u - \frac{c^2}{\Delta} p_o = (u - cn_x)$$

$$\dot{y} = v - \frac{c^2}{\Delta} q_o = (v - cn_y)$$

$$\dot{z} = -\frac{c^2}{\Delta} r = -cn_z$$

$$\Delta = \omega_o + up_o + vq_o = c(p_o^2 + q_o^2 + r^2)^{\frac{1}{2}}$$

$$r^2 = \frac{\Delta^2}{c^2} - p_o^2 - q_o^2$$

where u, v = wind components at level of interest

c = local speed of sound

n_x, n_y, n_z = unit normal components in the x, y, and z directions.

Recurvature (ray direction reversal) occurs when $(\Delta/c)^2 < p_o^2 + q_o^2$. In order to forecast recurvature and the need for smaller step size the following expression is used for the z ray "acceleration".

$$\ddot{z} = \left[\frac{c^3(p_o^2+q_o^2)}{\Delta^2} - c\right]c_z + \left[\frac{c^4(p_o^2+q_o^2)}{\Delta^3}\right]\left[p_o u_z + q_o v_z\right] .$$

3.7 Ray Tube Area

At each instant of supersonic flight, the aircraft emits a cone of rays, each of which is singled out by specifying an angle, ϕ. The set of rays which leave the aircraft at neighboring times, between t_A and $t_A + \Delta t_A$, and at neighboring angles, between ϕ and $\phi + \Delta\phi$, form a ray tube.

The total acoustic energy in a ray tube has been shown to be constant (for linear, inviscid processes) by Blokhintzev who formulated an invariant relating the ray tube area to the inverse square of the amplitude. This invariant is used in both the TRAPS and the BOOMAP2 programs.

The programs define the ray tube area as neither a horizontal section nor a cross section, but as a section cut by the wave phase surfaces within a unit time, i.e., a section normal to the wave normals.

Defined in this way, the ray tube area is always finite, and is a Galilean invariant. That is, it is a quantity whose value does not change when measured by an observer moving at any constant velocity. Since the amplitude of the sonic boom is clearly a Galilean invariant, as are the pressures, temperatures, densities, sound speeds, and other physical quantities in the Blokhintzev invariant, this definition is the most appropriate.

The program computes the area as a determinant (called a Jacobian) formed from partial derivatives of coordinates with respect to the ray parameters ϕ and t_A. These partial derivatives are found by integrating equations similar to the ones used to track the rays, and are in fact derived from them as will be discussed subsequently.

This technique is better than the alternative of actually tracking neighboring rays and computing the area of the figure formed by the endpoints, since over the distances, even rays which are initially very close can spread over considerable distances. Furthermore, area computations of that type are so sensitive to round-off errors in position that the error may be many times the actual area.

Specifically, the ray tube area is defined as the Jacobian, J, given by

$$J = \frac{\partial(x,y,z)}{\partial(\Psi,t_A,\phi)}$$

where ψ is the phase

(Ray tube area has units of length squared per unit time.) The Blokhintzev invariant alluded to earlier is simply

$$\frac{J\, p_o^2}{\rho_a\, \Delta\, c^2} = \text{constant.}$$

Along any ray the Jacobian value may be calculated by taking the partial derivatives of the ray tracing equations with respect to Ψ, t_a, and ϕ and interchanging the order of differentiation.

Since the ray bank angle, Φ, does not influence the position of the aircraft, $\partial x/\partial\phi$, $\partial t/\partial\phi$ and $\partial z/\partial\phi$ are initially zero. The remaining initial conditions are found by differentiating the wave number initial conditions with respect to ϕ

$$\frac{\partial p}{\partial \phi_o} = -\frac{\Delta_o}{c_A}\,[\cos(\mu)\ \cos(\phi)\ \cos(\theta) + \cos(\mu)\ \sin(\phi)\ \sin(\theta)\ \sin(\gamma)]$$

$$\frac{\partial q}{\partial \phi_o} = -\frac{\Delta_o}{c_A}\,[\cos(\mu)\ \cos(\phi)\ \sin(\theta) + \cos(\mu)\ \sin(\phi)\ \cos(\theta)\ \sin(\gamma)]$$

$$\frac{\partial r}{\partial \phi_o} = -\frac{\Delta_o}{c_A} - [\cos(\mu)\ \cos(\phi)\ \cos(\gamma)]$$

$$\frac{\partial \omega}{\partial \phi_o} = -u_o\,\frac{\partial p}{\partial \phi_o} - v_o\,\frac{\partial q}{\partial \phi_o} - w_o\,\frac{\partial r}{\partial \phi_o}$$

Similarly, initial conditions are obtained on the derivatives of x, y, z, Δ, ω, p, q, and r with respect to t_A. To differentiate with respect to t_A with Ψ fixed, the value of dx/dt along the ray, i.e. u + cp must be subtracted from $x'(t_A)$. Similar adjustments must be made for the other coordinates, y through r.

Since the third parameter defining the rays is the phase Ψ (which is identified with position ξ behind the nose and has the unusual dimension of length), initial conditions on derivatives with respect to it are not required. Rather, since the vectors $\partial(x,y,z)/\partial\phi$ and $\partial(x\ y,z)/\partial t_A$ are both expected to lie in the surface Ψ = const., the vector $\partial(x,y,z)/\partial\Psi$ is replaced with the normal vector $\nabla\Psi / |\nabla\Psi|^2$ or $-(p,q,r)/(p^2+q^2+r^2)$ without changing the Jacobian.

The Jacobian technique leads to a ray tube area that varies in a continuous manner as the ray is traced, and even the rate of change of area with position along the ray is continuous so long as the gradients of wind and sound speed are continuous in the atmosphere model. Where the gradients are discontinuous (and this occurs at each height at which either temperature or wind is input or taken from the Standard Atmosphere), the rate of change of area (but not the area) undergoes a jump. The amount of this jump is a continuous function of the ray normals, which are themselves continous.

The result of this is that the ray tube areas on the ground and the amplitudes are continuous functions of the ray parameters. Except when the ray tube area is zero, or at the edge of the carpet, they are also continuous functions of position on the ground.

3.8 Signal Propagation

In the linearized acoustic theory, the wave form of the pressure travels along the ray unchanged except for amplitude changes governed by the Blokhintzev invariant. At least below the mesopause, effects of viscosity and heat conduction are too small to seriously affect this concept.

Pressure waves of this amplitude are governed by a non-linear theory, and although the non-linear effects are small over any given region up to some tens of wavelengths in size, they do accumulate and are responsible for the typical N-wave profile of the direct sonic booms and the bulk of dissipitation of acoustic energy between the aircraft and ground.

In terms of supersonic flow, the sonic boom is "weak," and the program applies a weak shock tube theory due to G.B. Whitham to the propagation of the sonic boom in ray tubes. In general, an overpressure at a given point in the wave form so increases the air speed and sound speed at its location that it seems to overtake a lesser overpressure located ahead of it. The amount of the overtaking is governed by a quantity termed the age, which increases along a ray at a rate proportional to the amplitude, and inversely proportional, among other terms, to the square root of the ambient air density. The age is given by the expression

$$A(t) = .5\ (\gamma+1) \int_{t_a}^{t} \frac{\Delta^{3/2}}{(c^2 \rho_a J)^{\frac{1}{2}}} dt$$

(Age has units of length multiplied by time divided by the square root of mass.)

The shift in phase may be expressed as

$$\Psi' = \Psi + Ap_i(\phi,\Psi)$$

where

$$p_i(\phi,\Psi) = c_A \sqrt{\rho_A}\ M\ F(\phi,\Psi)$$

(F has units of length$^{\frac{1}{2}}$, p_i has units of mass$^{\frac{1}{2}}$ per unit time.)

When a section of the waveform actually overtakes one ahead of it, the choice among the three or more possible values of overpressures is resolved by fitting a shock (pressure jump), thereby cutting off the lobes of the overtaking and overtaken portions. To conserve mass, the shocks are so placed as to balance the area within the cutoff lobes using the so-called "equal area rule" (Figure 7).

The pressure far field signature is calculated in terms of the above quantities as

$$p(\phi,\Psi) = c\ (\Delta\rho_a)^{\frac{1}{2}}\ J^{-\frac{1}{2}}\ p_i(\phi,\Psi)$$

When the ray tube area reverses sign along a ray the geometric theory implies that the pressure is infinite at the point where the area is zero. This point is called a caustic point. Infinite pressures are, of course, contrary to reality and are a consequence of the failure of this theory.

In fields other than acoustics, such as water wave theory or optics to which ray theory applies, a more general theory known

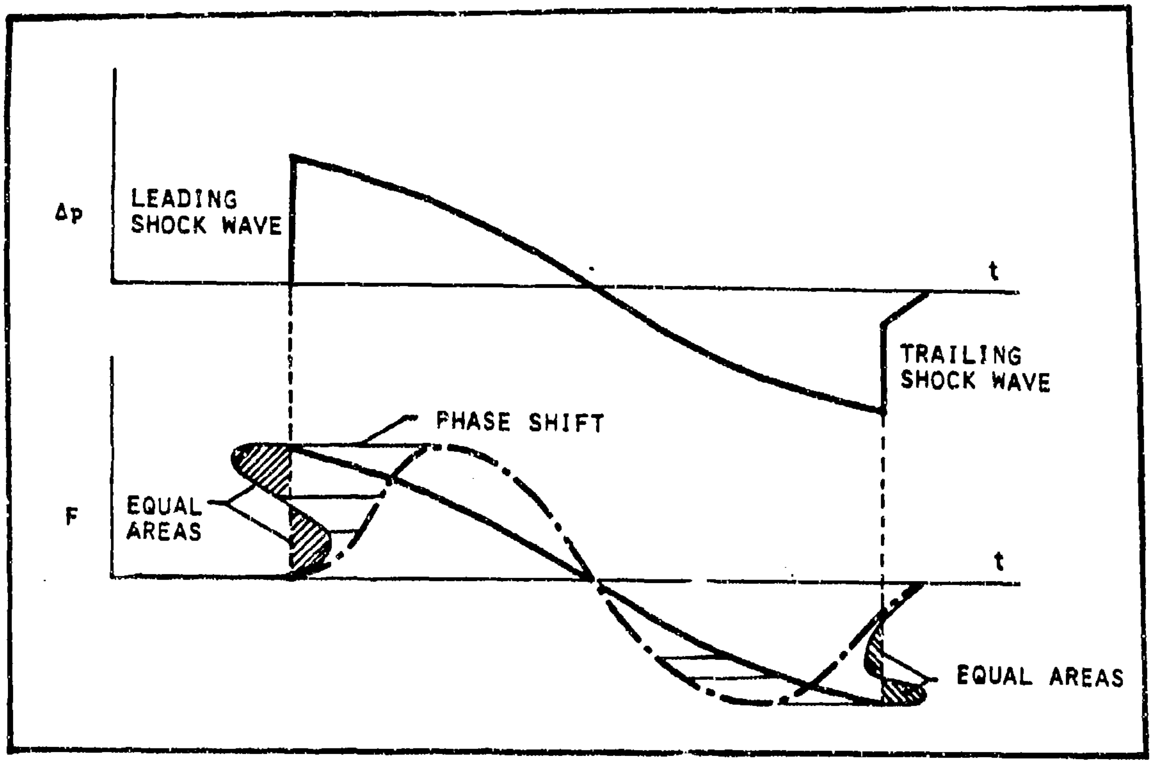


FIGURE 7. SIGNATURE AGING PROCESS ADAPTED FROM HAYES ET AL (1969).

as Uniform Asymptotic theory may be applied. Indeed, this more general theory holds for linearized acoustics as well, and can be used to determine the shape of the wave departing the caustic, given the shape of the wave approaching the caustic. After passage through the caustic, ordinary ray theory holds once again and the program may resume, now propagating the new signature. It is this technique which the BOOMAP2 program uses to continue the evolution of the sonic boom.

It is a conclusion of the Uniform Asymptotic theory, to whichever physical process it has been applied, that the Fourier components of the outgoing signal are the same as they would be expected to be from the naive ray theory, except that each one has been shifted forward one quarter wavelength. Since the shorter wavelength components advance less than the longer components, the shape of any complex waveform can change significantly.

This transformation is commonly known by the name of "90 degree phase shift" (since there are 360 degrees in a full wave cycle). Hence, there is a temptation to perform it by actually taking a finite Fourier transform, changing the coefficients, and inverting. However, even with the Fast Fourier Transform, this is an extremely inefficient procedure.

The reason lies in the shape of the input signal, which by the time of caustic passage has usually aged into a nearly N-wave form. The transform of the N-wave has two very thin peaks (logarithmic discontinuities) located where the jumps were (Figure 8). To resolve these peaks requires a number of very closely spaced points in their immediate vicinity. Elsewhere, the waveforms are smooth and such close spacing is extremely wasteful of computer resource. In particular, a much wider spacing should be used far ahead of and far behind the original waveform. But finite Fourier transforms require a uniform spacing of points, forcing a choice between inadequate resolution and waste of resources.

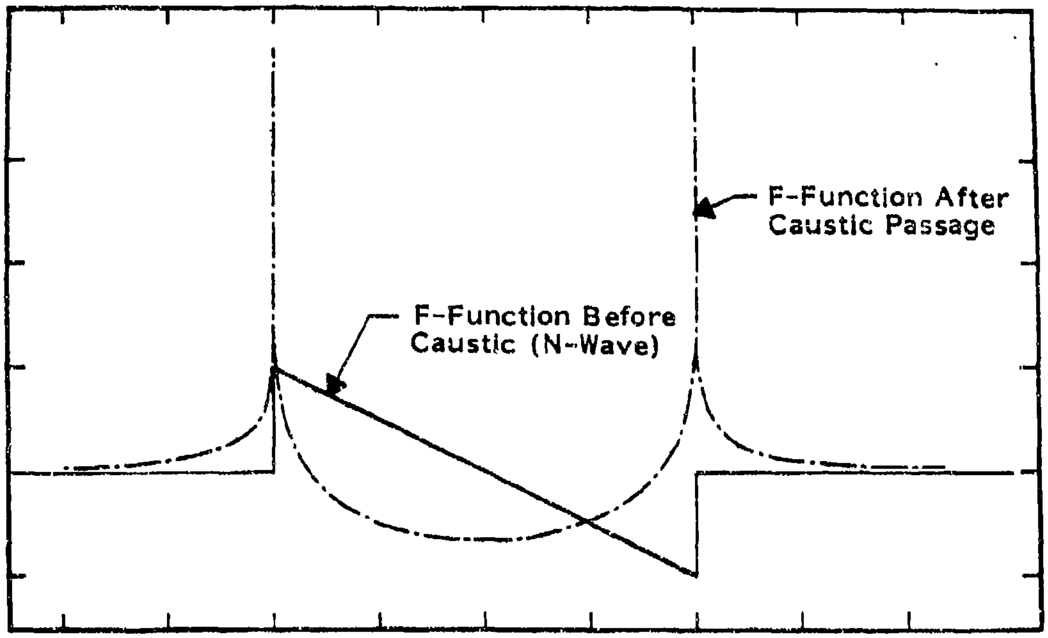


FIGURE 8. CAUSTIC TRANSFORMATION OF F-FUNCTION.

The program uses an alternative to the above Fourier techniques, called the Hilbert Transform. This is an integral transform with a singular kernel whose Fourier equivalent happens to be the 90 degree phase shift; it has the advantage that it may be evaluated at an arbitrary selection of points whose spacing may be chosen with the above principles in mind.

In the program, the sonic boom signature is taken through the following evolutionary steps:

(i) Compute the age until the ground or a caustic is encountered;

(ii) Age the signature and fit shocks as appropriate;

(iii) If at a caustic, perform the Hilbert Transform and create a new signature;

(iv) Continue with step (i) until final ground contact.

In this analysis, the Uniform Asymptotic theory must be regarded as an approximation in that the shocks of the N-wave indicate the operation of non-linear effects, and the theory applies to linear systems which is reinforced by the appearance of infinities in the Hilbert Transform of the N-wave. In reality, however, the N-wave with the shocks is an approximation to the actual signature. Since the sonic boom is weak, in the sense of supersonic flow theory, the shocks are not strong, well established features. Measurements often show a "rise time" for the shocks of between 1/30 and 1/10 of the length of the N-wave, presumably due to some form of turbulent dispersion. With such a "thick shock," the infinities in the wave form all disappear, and the Uniform Asymptotic theory, if carried out, would lead to finite overpressures up to and past the caustic surface. This

result places the validation of the Uniform Asymptotic theory on the same level as ray theory, as an approximation to the linear acoustic equations, and the validation of the linear theory as an approximation to the non-linear theory on the same level near the caustic as elsewhere.

If a caustic point lies near the ground, it is important to characterize the sonic boom signature at this location. There are three types of caustic points: a smooth caustic, a cusped caustic, and a perfect focus. The smooth caustic lies along a surface containing continuous focusing for a range of initial times and ray angles. The ground intersection is a line. A cusped caustic has an infinitesimal perfect focus along a curve intersecting the ground in a point. Similarly a perfect focus will (at most) intersect the ground in a point; it esults from a finite wave element focusing to a point. The program includes a model of the smooth caustic. It is the most frequent type and affects significantly larger areas than the other two types.

The signature calculated for a smooth caustic is based on the smooth caustic similitude solution developed by Seebass. This solution requires determining the relative curvature of the caustic surface in the direction of collapse with respect to the ray curvature. Th calculations proceed as follows:

Auxiliary rays are traced to determine the direction of ray tube collapse. The ray along which focusing was detected may be characterized by the time, t_o, and the ray bank angle, ϕ_o, at which it was emitted. The auxiliary rays are perturbed from the reference ray as follows:

Ray	Time	Orientation
1 (Reference)	t_o	ϕ_o
2	t_o	$\phi_o + \Delta\phi$
3	$t_o + \Delta t$	ϕ_o
4	$t_o + \Delta t$	$\phi_o + \Delta\phi$

where

$$\Delta\phi = \text{sine } (\phi) \times 0.5 \text{ degrees} = \text{sine } (\phi) \times 8.73^{-3} \times 10 \text{ radians}$$

$$\Delta t = \frac{\Delta\phi \frac{4.6 \text{ ACL}}{c_A}}{\sqrt{M^2 - 1}} \text{ seconds}$$

where ACL = aircraft length

c_A = speed of sound at the aircraft

At the focus the vectors from ray 1 to ray 3 and ray 3 to ray 4 are computed and designated $\vec{\Delta}_{13}$ and $\vec{\Delta}_{34}$ respectively. Additional focusing ray tubes are calculated as follows:

Summary of Raytubes to be Traced

Tube	ϕ	Origin t	Location	Focus Time
1. Original Focusing Tube	ϕ	t_o	$\vec{p}_o$	T_1
2. First Auxiliary	ϕ_1	$t_1 = t_o - \frac{\Delta s}{Mc_A}$	"$\vec{p}_o - \Delta s$ feet"	T_2
3. Second Auxiliary	ϕ_2	$t_2 = t_o + \frac{\Delta s}{Mc_A}$	"$\vec{p}_o + \Delta s$ feet"	T_3
4. Third Auxiliary	ϕ_3	$t_3 = t_o - \frac{2\Delta s}{Mc_A}$	"$\vec{p}_o - 2\Delta s$ feet"	T_4

$\Delta s = 800$ feet

$$t_j = t_o + \phi_{inc}\, \bar{v}_j\, (t_j - t_o)$$

$\bar{v}_j$ = average aircraft velocity between t_o and t_j

$$\phi_{inc} = - \frac{\vec{\Delta}_{13} \cdot \vec{\Delta}_{34}}{|\vec{\Delta}_{34}|^2} \frac{\Delta\phi}{v\Delta t}$$

v = aircraft speed at time t

The focus times for the four focusing ray tube are examined to assure that a smooth focus is being treated: $T_4 < T_2 < T_1 < T_3$. If not the focus is discarded (not a smooth caustic).

The points along the reference ray upstream of the focus are fitted with a circular arc to estimate the ray curvature at the focus, $\vec{\kappa}_R$. Similarly, the caustic curvature $\vec{\kappa}_C$ is calculated from the first three focusing ray tubes.

The relative curvature vector upon which the amplitude of the focus overpressure is calculated as

$$\vec{\kappa}_{rel} = \left[1 - \frac{\vec{\kappa}_R \cdot \vec{\kappa}_c}{\vec{\kappa}_c \cdot \vec{\kappa}_c} \right] \vec{\kappa}_c$$

and the relative radius of curvature is given by

$$R_{rel} = \frac{1}{| \vec{\kappa}_{rel} |}$$

In order to proceed with the calculations, the program now searches for a point on the reference ray for which the peak overpressure matches the peak calculated from the focus solution. This is implemented in an iterative process as follows. At a point sufficiently upstream of the focus the peak overpressure is calculated. The pressure coefficient, C_p, for the largest overpressure is calculated as

$$C_P = \frac{\Delta P}{2 \Gamma P}$$

The distance from the caustic along the ray to this reference point, S, is calculated by summing the arc segments. The distance normal to the focus is estimated as

$$Y \quad \frac{S^2}{.52rel}$$

This distance is now used to estimate focal zone boundaries (where the incoming signal matches the peak focal overpressure) first in the direction normal to the focus:

$$Y^* = \left[\frac{(0.1)^{4/5}}{0.39} \right]^4 \left[0.6 \; C_p \; Y^{1/4} \; R_{rel} \right]^{4/5}$$

and then in a tangential direction

$$X^* = \sqrt{2 R_{rel} Y^*}$$

If the selected point is more distant than X*, this procedure is repeated until a point at this distance is located (by interpolation as necessary). A detailed signature is then developed using the full Gill/Seebass solution for each shock in the solution. If the ground level lies between the focus and a distance X* upstream of the focus, the focus signature (scaled by the appropriate reflection factor) is taken as the ground level signature.

If the ground level is sufficiently far downstream of the focus the TRAPS postfocus solution discussed earlier provides an adequate representation of the ground overpressures. In order to assure that the ground level is sufficiently far downstream of the focus, the same criteria are employed as were used on the upstream side of the focus. The pressure coefficient corresponding to the peak pressure in the TRAPS focus solution is compared with the pressure coefficient from the peak focus overpressure. If the focus solution is larger the TRAPS postfocus solution is accepted. Otherwise, the focus solution is used as the ground level free field signature.

3.9 Implementation of Ray Tracing in BOOMAP2

At any given aircraft track time t, the aircraft position and velocity vectors are known, and the acceleration vector and interpolation coefficients have been derived. The admittance ellipse at ground level, defined in Section 3.6, determines the range of the initial ray bank angle which will reach the ground. Starting with the largest negative value, rays are traced at increments of 1° if the aircraft is above 15,000 ft and 2° if

the aircraft is below 15,000 ft, until the largest positive value of ϕ is reached.

If during the tracing of a ray, a caustic is encountered in the "ground zone", defined as the region 1000 ft above the ground to 1500 ft below the ground, the ray history and caustic location are stored, the ray tracing terminated and the next value of ϕ is traced. After all possible ϕ values have been traced for the time t, the stored caustic locations are used to estimate no more than two ray bank angles ϕ, at which the caustic surface either crosses the ground or is closest to it.

Starting at these estimated ϕ values, rays are traced at ϕ intervals of $\pm 0.1°$ or $\pm 0.2°$ (depending on aircraft altitude) until the caustic is no longer in the "ground zone". Using the theory outlined in Section 3.8 the focal zone width is estimated for an angle ϕ. If the ground is within the focal zone, the focus overpressure and signatures are used, otherwise the original TRAPS solution is used.

The relative curvature of the ray and the caustic surface are used in calculating the focal width. The tracing of the auxiliary ray tubes to define the caustic curvature necessitate interpolation beween at least three adjacent aircraft track times. If the original aircraft position and velocity vectors are "noisy", the acceleration and jerk vectors (even after smoothing) can show major variations with time, and hence, the caustic surface can be irregular or form cusps. The caustic curvature may show major variations with ϕ angle and give unrealistic large values of focal zone width. An arbitrary limit was chosen, so that if the focal zone width extended more than 2500 ft above the ground, the ray was rejected. In addition, the overpressures calculated on the ground for all ϕ values (both focus and TRAPS solutions) are checked for singularities which give too large a variation with ϕ, and these rays are rejected.

3.10 Calculation of CSEL from Signatures

Typically, there is a simple relationship between overpressure and C-weighted Sound Exposure Level (CSEL) for sonic boom signatures, which are sufficiently far away from a focus (Ref. 9)

$$L_{CE} = L_{PK} - 26$$

However, in the focal and post-focal zones, the pressure signature changes radically (Figure 9) and a more accurate estimate of CSEL may be required, which is done by performing a Fast Fourier Transform (FFT) of the signature, applying a C-weighted filter to the spectrum and integrating to give CSEL.

The signature, produced by BOOMAP2, gives pressures (including shocks) at irregularly spaced time intervals. Based upon the parametric study of waveforms in Appendix C, Ref. 9,

(a) the effect of the rise time of the shocks on CSEL is insignificant;

(b) A Nyquist frequency of 1000 Hz is adequate (i.e. time interval = 0.5 milliseconds).

The BOOMAP2 signature is therefore modified by first identifying the shocks and separating them by 0.5 milliseconds. The time of maximum overpressure is used to define a new time variable, spaced at equal intervals of 0.5 milliseconds, and the pressure signature is interpolated at these times. An FFT is performed, after extending the signature with zeros to the necessary (power of 2) number of points. An analytical C-weighted filter is applied to the spectrum and the spectrum is then integrated to give the CSEL value.

3.11 Calculation of Scratchpad Contours

For the scratchpad contour plots to be generated, the user must first select the sorties to be processed. The BOOMAP2 program then accesses the database containing the rays associated with the selected sorties. All rays emitted from the aircraft at the same time are then read from the database and sorted by angle ϕ. This processing continues until all the rays for a selected sortie are processed, or a 4-1/2 second time gap is found. This is known as a flight segment.

If no caustic rays are found in the flight segment, then a scratchpad contour plot will not be generated for that flight segment. The flight segment is then appended to a temporary file only if it contains caustic rays. This process is repeated until all the selected sorties are processed.

After the selected sorties are processed and the temporary file is created, the BOOMAP2 program then reads an entire flight segment. It then converts the pressure in pascals to either the maximum overpressure in psf or the maximum sound pressure level (SPL) depending upon which metric the user specified. At the same time the maximum pressure for the entire flight segment is found. Based on this, ten contour levels are selected either in dB or psf. If the maximum SPL has been selected, the contour levels are in intervals of 2.5 dB. If overpressure in psf has been selected, the contour levels are in a ratio of two to one (0.25, 0.5, 1, 2, ...).

The next step divides the flight segment into sections based on initialization time from the aircraft. These sections are then searched for the selected contour level. If the selected contour level is found, a linear interpolation is done

to find the x, y location of that pressure; up to four x, y points may be returned for each time slice. If no points are found for the flight segment, a search for the next contour level begins. This processing continues until all ten contour levels have been searched or points have been found in at least two different time slices for the flight segment. Then, the points that have been identified are sorted on termination time in order to allow the outer edges of the contour to be connected in increasing x and y ground locations. Once the points are connected, the contour is plotted on the scratchpad. If possible, three contour levels are plotted on each scratchpad. This processing continues until all selected sorties have been processed.

3.12 Calculation of Average Overpressure Values for GPCP Contouring Program Processing

The ray tracing code (see Section 3.9) results in calculated overpressure values at an irregularly-spaced array of ground positions. The GPCP contouring program requires as input that the overpressures be defined at grid points that are equally spaced in a rectangular pattern. Thus, it is necessary to develop algorithms to calculate values at the GPCP grid points that are based on the calculated ray tracing overpressures in the vicinity of each grid point. Each grid point may be influenced by none, one, or many calculated ray values.

The gridding algorithm for determining values at the GPCP grid points requires three arrays: a master array, an accumulator array and a counter array. Each of these arrays is dimensioned 102 by 102 with each cell representing a grid point. The spacing between grid points is set at 2500 feet. The combat training range geographic center is located in the center of

each array allowing 125,000 ft in each direction from the range center.

The first step in the gridding algorithm is to initialize the master grid to a value of 1.0 pascals. This reduces the extent of the steep contours resulting from an otherwise zero background.

The rays that coincide with the selected sortie are then read from the database, generated by the BOOMAP2 program, one sortie at a time. The data is then sorted by ϕ angle. If there are any gaps in the data greater than two degrees, a linear interpolation is used to fill the gap in one degree increments. The rays for the selected sortie are then sorted on termination time.

These rays are then processed in 5.5 second time slices. Each ray in the time slice is mapped to the four closest grid points to where it terminates. The accumulator array is then updated by adding the squared pressure of the ray, in pascals, to the current value of the grid point. The four corresponding counter array grid points are then incremented by a value of one. This processing continues until all the rays for the time slice have been processed.

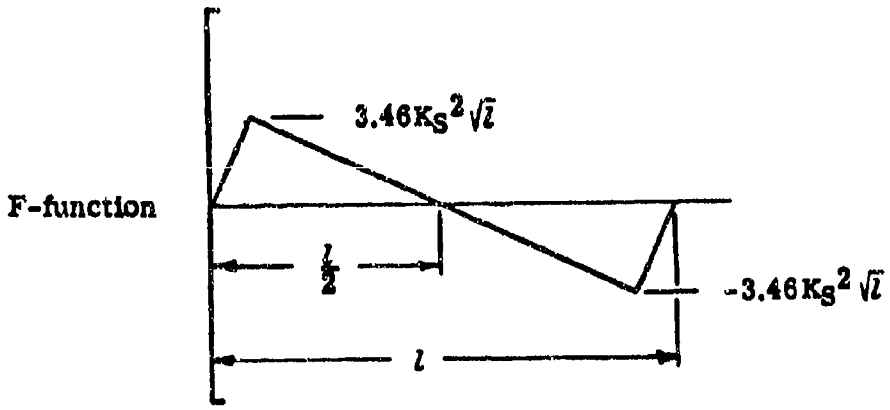
After 5.5 seconds have elapsed, the master grid array is then updated by dividing the accumulator array by the counter array and adding it to the current value of the master array. The accumulator array and the counter array are then zeroed. This processing is continued until all the rays for a selected sortie are processed.

After the selected sortie has been processed, the above process is repeated until all of the user's selected sorties have been processed. Once this is done, the master grid is then divided by the number of supersonic sorties and the square root is taken to get the RMS value. The result is converted to CSEL values using the following formula, (20 * log10(n) + 68). At this point, the master grid values can be fed into the GPCP contouring program.

4.0 AIRCRAFT F-FUNCTIONS FOR THE MODIFIED TRAPS PROGRAM

As discussed in Section 2, a sonic boom propagation program must be provided with a description of the disturbance of the atmosphere generated by the supersonic aircraft. It may be described in terms of the overpressure wave form that an observer near the aircraft would measure as the aircraft flies by or, equivalently, in terms of a theoretically derived F-function defining the flow near the aircraft. Both the original TRAPS program and the BOOMAP2 computer program use the latter approach.

The F-function is developed from consideration of the aircraft geometry and its lift distribution (see more detail in Section 2). The F-function can generally be separated into area and lift components. The original TRAPS program provided for the F-function described in terms of these two components. However, the BOOMAP2 code employs a simplified F-function based on a method developed by Carlson (Reference 4). This F-function can be characterized as an N-wave with a rise time much shorter than the duration of the entire disturbance. The peak amplitude of the F-function is then taken as a function of the aircraft shape factor, K_S shown below:



In the modified TRAPS program implementation, the F-function is characterized as having a rise time 1/100th the duration of the entire disturbance. However, rise time is not critical in the overpressure calculations since it is the area of the F-function displayed that is important and this area is independent of the rise time.

The approach used to develop simplified F-functions follows that of Carlson. Thus, K_s is estimated from curves showing K_s as a function of K_L (using Figure 4 of Reference 4). K_L is defined as follows:

$$K_L = \frac{\sqrt{M^2 - 1}\, W \cos \gamma \cos \theta}{1.4 p_v M^2 l^2}$$

Based on this approach, the BOOMAP2 program has the F-functions as shown in Table 1. It lists the aircraft in the current program together with typical aircraft lengths and weights, together with typical K_L and K_s functions.

F-functions for new aircraft can be developed following the procedures of Carlson, but these procedures are a simplification of actual situations, because the F-functions change with aircraft accelerations and also vary with altitude and speed. However, these changes generally are small compared with other uncertainties in the calculations, and are not critical unless one is concerned with developing a detailed calculation for specific test conditions, a situation beyond the routine application of the BOOMAP2 program.

TABLE 1

TYPICAL AIRCRAFT LIFT PARAMETER AND SHAPE FACTOR VALUES FOR SONIC BOOM CALCULATIONS

AIRCRAFT	LENGTH FT	WEIGHT KLBS	TYPICAL KL	TYPICAL KS
B-1B	147.0	453.0	0.0060	0.0910
F-4	58.2	56.0	0.0040	0.0880
F-5	46.6	19.6	0.0025	0.0642
F-8	54.5	32.3	0.0035	0.0870
F-14	62.7	56.7	0.0040	0.0873
F-15	63.8	42.3	0.0030	0.0838
F-16	47.6	23.3	0.0030	0.0838
F-18	56.0	49.3	0.0050	0.0900
F-20	46.5	26.1	0.0035	0.0643
F-101	71.1	48.4	0.0030	0.0860
F-104	54.8	21.4	0.0025	0.0642
F-105	64.2	42.7	0.0030	0.0869
F-106	70.8	34.2	0.0020	0.0840
F-111	75.5	95.0	0.0050	0.0892
SR-71	107.4	161.0	0.0100	0.0870
T-38	46.3	11.2	0.0020	0.0642

5.0 SELECTION OF THE COMPUTATIONAL PROGRAM TRAPS FOR SONIC BOOM CALCULATIONS

The calculation for sonic booms for general maneuvers in a real atmosphere is sufficiently complex to require a computerized model. A number of computer models exist, all of which rest on the identical theory for nonfocusing cases. Major differences lie in the computational philosophy and added features.* Four existing models were considered for the current program:

A. SABER (Ref. 12) developed by the J. H. Wiggins Company for USAF WSMC, which is descended from the Thomas program.

B. TRAPS (Ref. 3) developed by the NOAA Air Research Laboratory has its philosphical and conceptual origins in the ARAP program.

C. FOBOOM (Ref. 13) developed by Wyle Laboratories is an extension of the THOMAS program which can compute boom signatures at focal zones.

D. SABERII (Ref. 14), an evolutionary development of the WYLE/MSFC model for applications to Space Shuttle ascent.

Three areas differ among the four models. They are the computational approach, treatment of focal zones, and user/system features. The most important for the current application was considered the computational approach and focal zone treatment, since the user/system features would need adaptation from any of the existing systems. A simplified comparison of the models is shown in Table 2. After evaluation of the programs, the TRAPS program was selected for two reasons: (a) TRAPS uses

*Virtually all BOOM models are "descendents" of either the ARAP (Ref. 10) or Thomas (Ref. 11) models.

TABLE 2. CAPABILITIES OF SONIC BOOM MODELS.

	Computers Models				Carlson Simplified (NASA)	Programs Needs
	FOBOOM (WYLE)	TRAPS (NOAA)	SABER (WSMC)	SABER 2 (WSMC)		
Primary Boom	●	●	●	●	○★	●
Focus At Ground	●			●		●
Post-Focus Boom		●				●
Vertically Turning Rays		●	●	●		
Multiple Booms		●	○	○		
General Maneuvers	●	●	○	○		●

● Full Capability

○ Partial/Incomplete

★ Steady flight only

a superior scheme for the analytic formulation for ray properties, (b) the TRAPS program is the only program that allows calculation of postfocus boom. The major drawback of the TRAPS program was the lack of means for calculating overpressures at focus. It was decided that this could be remedied by using the approach introduced in the FOBOOM program for calculations at focus.

After decisions were made to use the TRAPS program, errors were encountered in the existing TRAPS program. These were review d by the author of the program, Dr. Albion Taylor, who then developed appropriate corrections to the program. On this basis, the modified TRAPS program provides answers that differ from the original TRAPS program calculations.

6.0 COMPARISON OF SONIC BOOM PROGRAM RESULTS WITH OTHER CALCULATIONS

This section presents some comparisons of the results with the modified TRAPS and BOOMAP2 programs compared with other programs, particularly the FOBOOM program, and with some field measurements. Table 3 presents some results for an F104 aircraft in level flight and simple maneuvers comparing the TRAPS and FOBOOM programs. The upper portion compares results from the TRAPS and FOBOOM programs in which both an F-function derived from a nearfield signature was used as well as the simplified Carlson F-function with $K_S = 0.07$ (see Section 4.0) with field measurements. The lower portion of the table compares calculated results for a constant speed turn and a constant acceleration dive.

For the first case, the field measurements were made at Edwards AFB in 1974, and the result quoted is an average of 37 measurements. Using FOBOOM, the effect of the measured winds and non-standard atmosphere was estimated to be small. The computed values shown in Table 3 are for no winds and standard atmosphere. The variation with altitude of overpressure is shown in Figure 9 and the signature duration in Figure 10, using the F-function from the near field signature in both FOBOOM and TRAPS. The variation of the waveforms with altitude is shown in Figure 11 for TRAPS and Figure 12 for FOBOOM.

The general results from these and other comparisons indicate that the overpressure results calculated by FOBOOM and TRAPS agree within approximately ± 5 percent. However, the durations calculated by the TRAPS program generally are consistently higher than those of the FOBOOM program by approximately 20 percent. The detailed reasons for this difference were not identified in this study.

For the cases shown in Table 3, there is essentially no difference between the results from modified TRAPS and BOOMAP2.

TABLE 3
COMPARISON OF SONIC BOOM PROGRAM CALCULATIONS FOR F104 AIRCRAFT IN LEVEL FLIGHT AND SIMPLE MANEUVERS*

Flight Condition Mach No	Alt, ft	F-Function	Program	Ground Height, ft	Maximum Overpressure, psf +	−	Boom Duration msec.
1.32	31,200(1)	--	Field Meas.	2,300	0.524	---	97
		Near field	FOBOOM	2,300	0.571	−0.448	71.2
		Near field	TRAPS	2,300	0.556	−0.471	76.8
		Carlson	FOBOOM	2,300	0.626	−0.626	87.9
		Carlson	TRAPS	2,300	0.616	+0.616	93.1
		Carlson	Simpl. Method	2,300	0.634	--	--
1.15	30,000(1)	Near field	FOBOOM	0	0.583	−0.485	91.2
		Near field	TRAPS	0	0.587	−0.426	96.8
		Carlson	FOBOOM	0	0.6[illegible]	−0.660	117.3
		Carlson	TRAPS	0	0.673	−0.673	110.4
1.7	36,000(2),(5)						
	φ = +30°	Carlson	FOBOOM	0	0.323		72.4
			TRAPS	0	0.370		84.9
	φ = 0°	Carlson	FOBOOM	0	0.561		79.5
			TRAPS	0	0.559		84.5
	φ = −30°	Carlson	FOBOOM	0	1.32		96.2
			TRAPS	0	1.24		94.6
	φ = −40°	Carlson	FOBOOM	0	-- (3)		--
			TRAPS	0	0.686(4)		102.5
1.15	25,000(6)						
	φ = 0	Carlson	FOBOOM	20,000	2.07		63.8
				15,000	1.49		72.0
				10,000	1.30		77.4
				5,000	1.24		81.3
				0	1.26		84.6
	φ = 0	Carlson	TRAPS	20,000	2.12		74.5
				15,000	1.51		82.6
				10,000	1.30		87.8
				5,000	1.20		91.6
				0	1.16		94.6
	φ = 0	Carlson	FOBOOM	20,000	2.03		64.2
				15,000	1.45		72.5
				10,000	1.27		78.0
				5,000	1.22		82.0
				0	1.23		85.3
	φ = 0	Carlson	TRAPS	20,000	2.08		84.9
				15,000	1.48		83.1
				10,000	1.27		88.4
				5,000	1.17		92.2
				0	1.13		95.23

* All calculations assume no reflection at the ground

(1) Straight and level flight
(2) Aircraft turning at rate of 1.9425 degrees/sec
(3) FOBOOM calculates focus at 7085 ft above ground
(4) TRAPS calculates focus at 7254 ft above ground
(5) φ is the azimuth angle of the merging ray. φ = 0 is directly below the aircraft
(6) Aircraft accelerating at 4 ft/sec^2 at dive angle of 27°

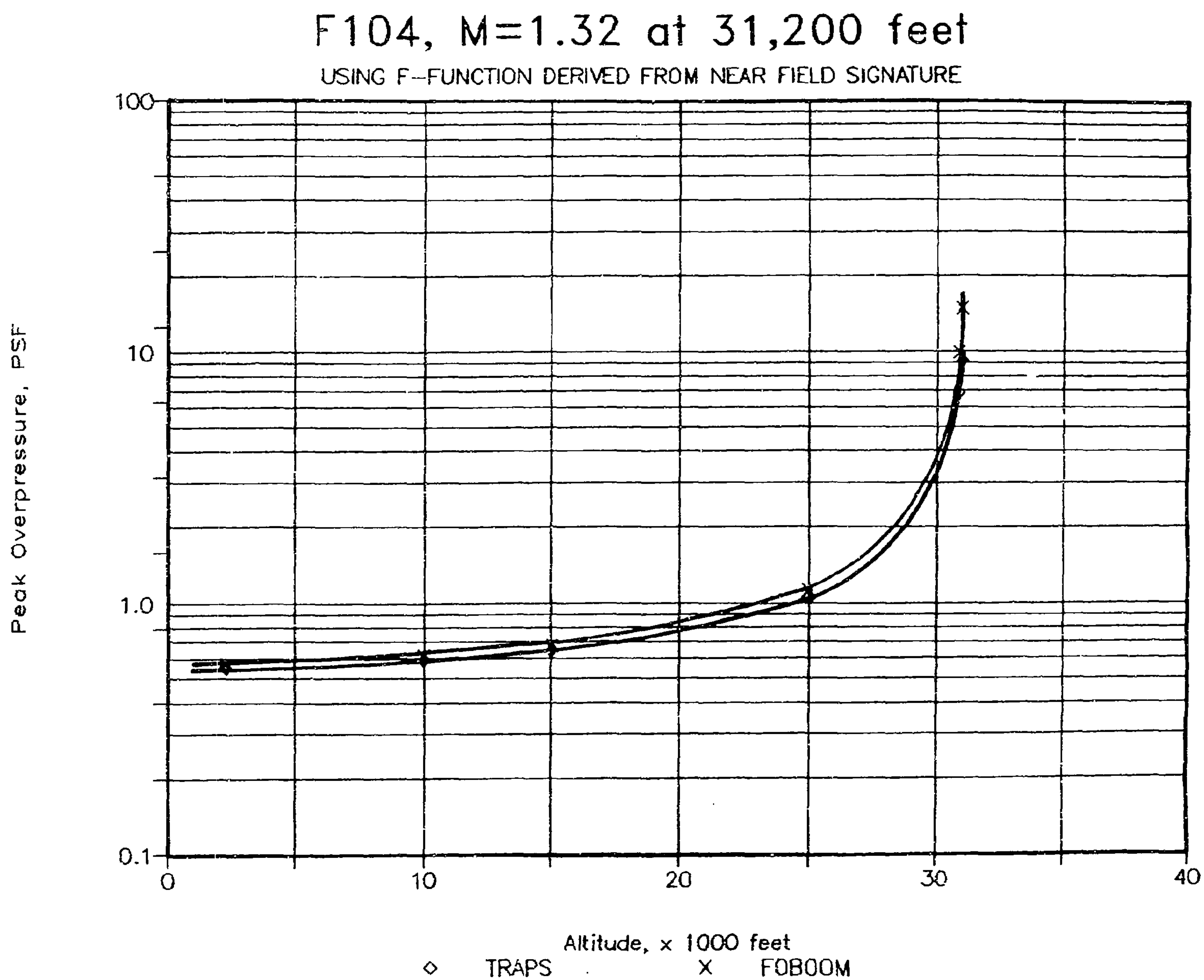


FIGURE 9. VARIATION OF OVERPRESSURE WITH ALTITUDE FOR F104 IN LEVEL FLIGHT.

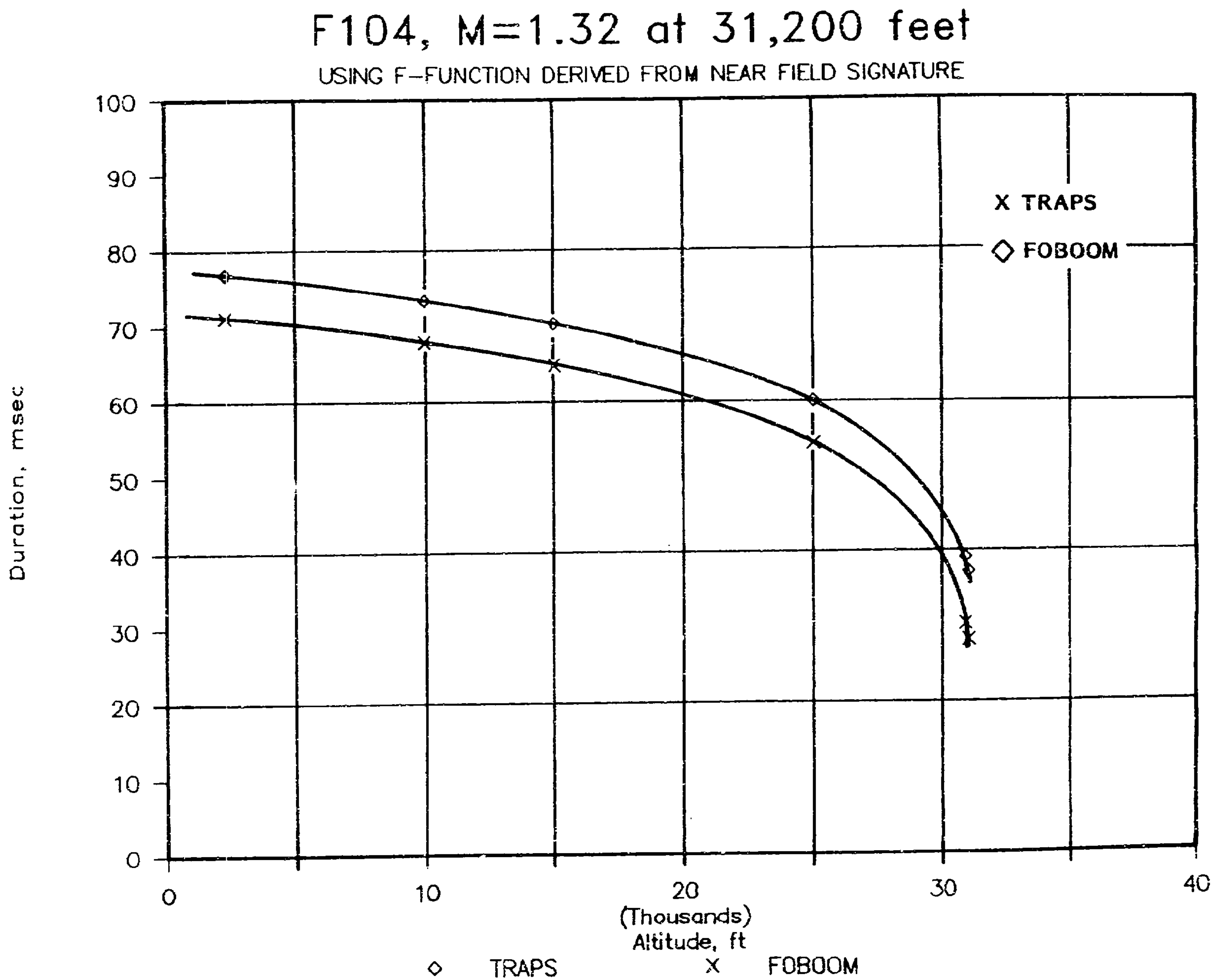


FIGURE 10. VARIATION OF SIGNATURE DURATION WITH ALTITUDE FOR F104 IN LEVEL FLIGHT.

F-104 EDWARDS F-Fn, M=1.32 @ 31,200 Ft.

2/17/87 TRAPS,Variation w/Ground Height

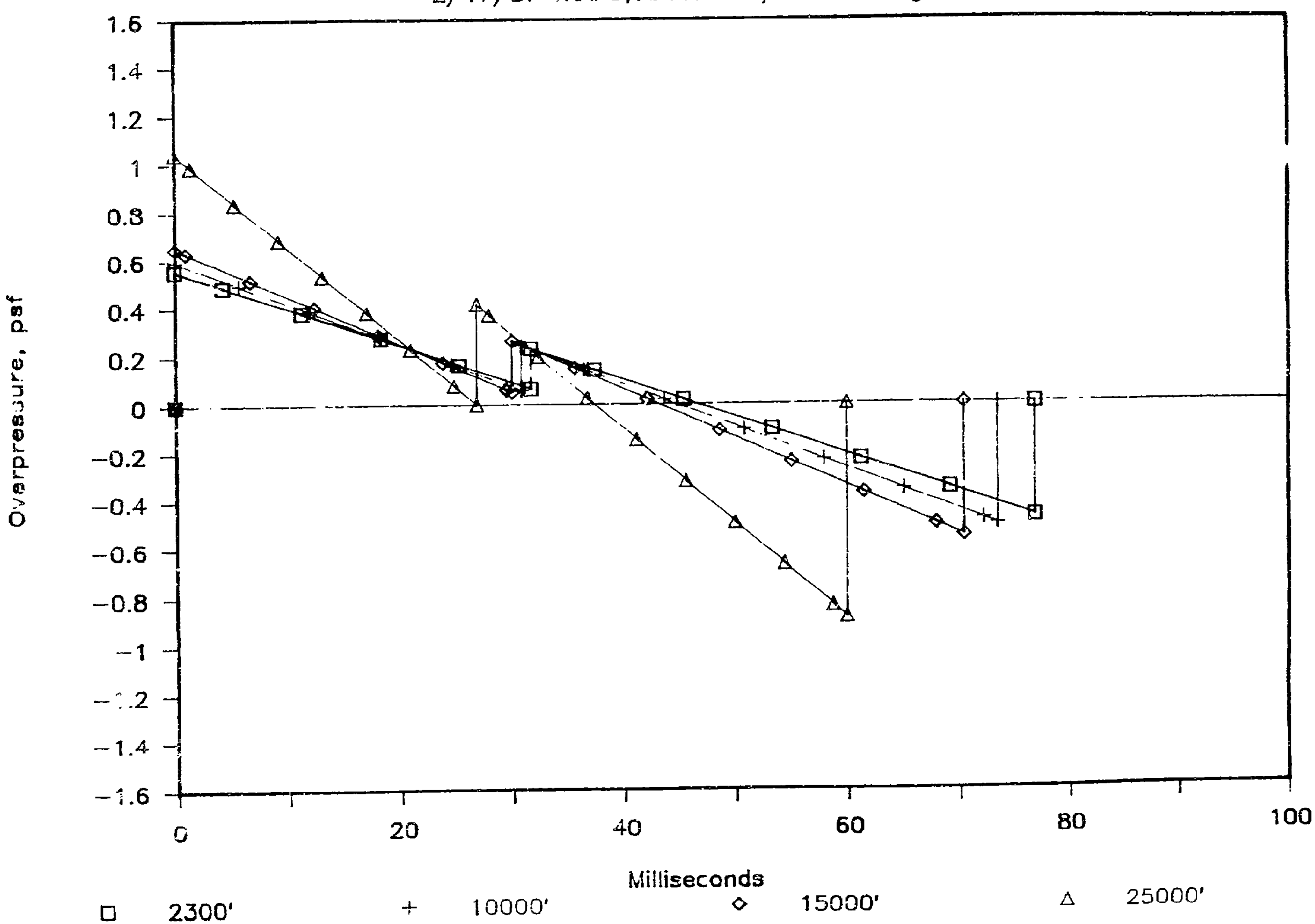


FIGURE 11. VARIATION OF SIGNATURE WITH ALTITUDE FOR F104 IN LEVEL FLIGHT -TRAPS PROGRAM.

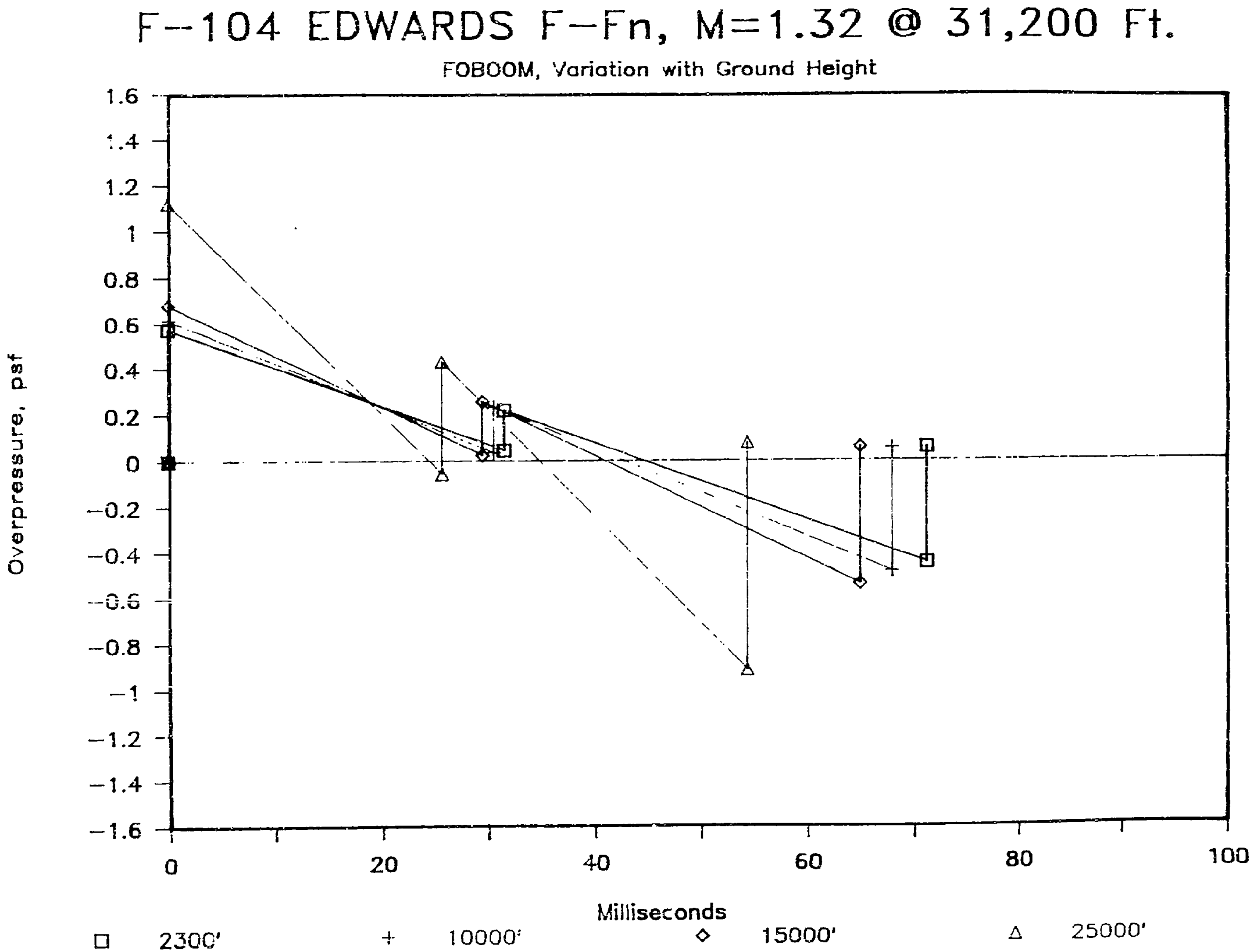


FIGURE 12. VARIATION OF SIGNATURE WITH ALTITUDE FOR F104 IN LEVEL FLIGHT -FOBOOM PROGRAM.

The effect of using displacements in TRAPS and velocities in BOOMAP2 as primary flight data input are negligible for steady state motion of the aircraft.

TRAPS, does not calculate the overpressure at or near a focus, and for this, comparisons must be made between FOBOOM and BOOMAP2. Table 4 compares FOBOOM and BOOMAP2 results for an F104 in level flight, M = 1.154 at 25,000 ft, accelerating at 4 ft/sec^2. The ground is at 1000 ft, ground reflections are included and Carlson's F-function is used. FOBOOM does not predict overpressure below a focus, but the results in the focal region are within 6%, with the TRAPS results consistently higher than those from FOBOOM. The focus altitude is also shown in Table 4, TRAPS predicts a focus approximately 80 ft higher than FOBOOM.

Table 5 compares the results for an F104 in a level turn at M = 1.7, with a turn rate of 1.9425 degrees per second (turn load factor = 2g), with the ground at either 0 ft or 1000 ft. In this case, the caustic surface is very steep, with a focus location at 1150 ft for $\phi = -34.2°$ and a slope of approximately -1200 ft/degree.

The calculation of the caustic surface curvature in the direction of the ray tube collapse is not always possible for every angle selected, because either the caustic is cusped (not included in BOOMAP2) or the focus on one of the auxiliary ray tubes does not exist. This may lead to gaps in the results. For instance, in Table 5 between $\phi = -32°$ and $\phi = -34°$, no overpressures were calculated at 0 ft, because of the steepness of the caustic surface. However, sufficient rays are traced to give a good representation of the focus.

The BOOMAP2 and FOBOOM results for the ground at 1000 ft, agree within 7 % near the focus. The comparison for the ground at

TABLE 4

COMPARISON OF FOBOOM AND BOOMAP2 PROGRAM CALCULATIONS FOR F104 AIRCRAFT IN LEVEL FLIGHT ACCELERATION

Ray Bank Angle	Overpressure at 1000 ft (psf)		Focus Altitude (ft)	
	BOOMAP2	FOBOOM	BOOMAP2	FOBOOM
0°	7.448	7.026	985	907
4°	7.040	6.926	1048	964
8°	6.665	6.400	1234	1152
10°	6.366	6.186	1375	1296
11°	6.225	5.912	1547	1469
12°	6.115	5.912	1547	1469
15°	5.652	5.542	1865	1786
18°	4.645	--	2257	--
21°	3.622	--	2725	--
24°	2.845	--	3270	--
27°	2.226	--	3894	--
30°	1.706	--	4601	--
33°	1.236	--	5394	--
35.3°	0.734	--	6053	--

NOTES:

F104, M = 1.154 at 25,000 ft, level flight, Acceleration = 4 ft/sec^2.
Ground = 1000 ft, with reflection factor of 1.0.
Carlson's simplified F-function used.
$\phi = 0$ lies vertically below the aircraft.

TABLE 5

COMPARISON OF FOBOOM AND BOOMAP2 PROGRAM CALCULATIONS FOR F104 AIRCRAFT IN A LEVEL TURN

Ray Bank Angle	Overpressure at 0 ft (psf)		Overpressure at 1000 ft (psf)	
	BOOMAP2	FOBOOM	BOOMAP2	FOBOOM
50°	0.379	0.302	0.393	0.336
40°	0.594	0.486	0.602	0.516
30°	0.752	0.628	0.760	0.652
20°	0.890	0.768	0.896	0.808
10°	1.015	0.936	1.019	0.966
0°	1.137	1.096	1.138	1.122
-10°	1.277	1.248	1.272	1.296
-20°	1.508	1.386	1.484	1.548
-30°	2.509	2.014	2.277	2.384
-32°	3.829	2.072	3.017	3.112
-33°	--	2.092	3.722	4.054
-34°	6.833	8.0*	8.300	8.910
-34.2°	5.814	--	8.293	--
-34.4°	--	--	8.287	8.42
-34.6°	--	--	8.307	--
-34.8°	--	--	6.739	--
-35°	3.773	--	5.775	--
-36°	2.794	--	3.538	--
-37°	2.245	--	2.663	--
-38°	1.879	--	2.154	--
-40°	1.410	--	1.557	--
-45°	.807	--	.862	--
-50°	.460	--	.494	--
-52.5°	.270	--	.271	--

NOTES:

F104, M = 1.154 at 36,000 ft, level flight. Turn Rate = 1.9425°/sec.
Ground = 0 ft and 1000 ft, reflection factor of 2.0.
Carlson's simplified F-function used.
ϕ = 0 lies Directly below the aircraft, with ϕ positive towards the center of the turn.

* Value from Ref. 15.

0 feet is incomplete in the focal region. FOBOOM gives a slightly different focus location than BOOMAP2, and hence, the angle at which the focus occurs on the ground differs from those selected for BOOMAP2. As Table 5 shows, the maximum value predicted by FOBOOM (Ref. 15) is 8 psf, 17 percent higher than BOOMAP2 results.

7.0 RECOMMENDATIONS FOR FUTURE WORK

7.1 Analytical Framework for Modified TRAPS Program

The basic documentation for the original TRAPS program (Ref. 3) provides a good overall discussion of the major features of the analysis approach incorporated in the TRAPS computer program. However, the documentation is incomplete in that the analytical expressions are not fully described which makes it exceedingly difficult to reconstruct the analytic framework from the computer program alone. The absence of a detailed mathematical description handicaps attempts to check the validity of the theoretical model and to extend the analytic approach to cover features missing from the original program. This lack is particularly unfortunate, because the basic TRAPS analytical approach gives every evidence of being superior to those utilized in earlier ray tracing models.

It is therefore recommended that the theoretical basis for the TRAPS program be developed and documented in detail. The best person to do this would be, of course, the original author of the TRAPS program, Dr. Albion Taylor. Such documentation would not only provide a basis for the detailed evaluation of the TRAPS program in handling various types of sonic boom situations, but would also provide a basis for possible extension of the TRAPS program to cover sonic boom situations that were not of immediate interest in the current program, but which may be of vital importance in other applications. For example, the capabilities of the TRAPS program to handle rays that have risen to a high altitude and returned to the ground were not of interest in the current application, but may be vital in future applications of the program of interest to the Air Force as well as to other users. Also, the lack of analytic formulation limits the rigorous comparison of the program predictions with the results of other programs or of field experiments.

7.2 Extension of the TRAPS Analytic Framework to Include Focus Signatures and Overpressures

None of the existing ray theory programs (including the TRAPS program) predicts the overpressure and wave signature at focus as part of their original mathematical development. The available programs that can handle this situation (FOBOOM and the modified TRAPS program) incorporate an approach to estimating the signature and overpressure that is, more or less, "grafted" on the basic program. This grafting process and the assumptions inherent in it lead to potentials for inexact calculations and, perhaps, oversimplifications. It is recommended that serious effort be given to extending the theoretical basis of the original TRAPS program to include a consistent analytic model for computing the overpressure and wave signatures at sonic boom focus locations.

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APPENDIX A

Sample BOOMAP2 Program Output

This appendix provides a sample of the BOOMAP2 computer program output based upon analysis of the MOAOPS library tapes for Luke Air Force Base. Figure A-1 lists the missions included in the analysis. At the end of the figure, the number of supersonic flights is listed, together with the number of boom-producing flights. These figures are based upon the telemetered Mach numbers, applying criteria derived from the steady flight Carlson equations.

At the end of Figure A-1, the total supersonic time and total boom-producing time are also listed. One set of figures is based upon the telemetered Mach number. The other set of figures is based upon a Mach number calculated from the ground velocity and the standard day temperature. Both set of figures are based upon criteria assuming steady flight (Carlson equations). All of the statistics for boom-producing flights and times listed at the end of Figure A-1 are approximate since they are based upon steady flight assumptions. In the detailed BOOMAP2 analysis, using the modified TRAPS ray-tracing program, the total boom-producing time may be quite different since the BOOMAP2 calculations do take into account accelerations and turns.

Figure A-2 presents various statistics for the geographic location, aircraft altitudes, Mach numbers and sound levels (with sound levels calculated from the Carlson equations). Figure A-3 presents information on the geographic location of supersonic flights.

Figure A-4 provides a sample of the "scratchpad" for one flight that generated a focus sonic boom. Because of the crude contouring program employed, the resulting display of the overpressure contours is simplified.

Note that the geographic location of the calculated maximum overpressure is shown on the scratchpad plot. The information on the geographic location of the maximum overpressure is collected from each scratchpad and used to generate a map showing the location of all focus booms for the MOAOPS library set under study (see Figure A-7).

Figure A-5 shows the geographic location of the flight tracks for all supersonic aircraft activity (as based upon reported Mach number). Figure A-6 shows the flight tracks that were likely to produce sonic booms that reached the ground (based on the cut-off equations of Carlson).

Figure A-7 shows the geographic location of the maximum overpressures resulting from focused sonic booms. For each of the geographic locations shown, there is a corresponding scratchpad which provides information about the flight that produced the focus boom.

Figure A-8 shows sonic boom noise contours for Luke AFB. Figure A-8 shows the average C-weighted sound exposure level contours. Contours of average maximum overpressure in pounds per square foot (psf) can also be produced by BOOMAP2.

SOURCE LISTING:

```
    TITLE LUKE RUN OF ENTIRE LIBRARY
[illegible]  SITE LUKE
3:  DATE ALL
4:  TIME ALL
5:  AIRCRAFT ALL
6:  MACHTRK 480000
7:  BOOMTRK 4[illegible]000
8:  CONTOUR F[illegible]EL,480000, 95., 100., 105., 110., 115., 120.
9:  STATS
```

TA[illegible] 1/ 1

SITE LOCATION	[illegible]SE [illegible]GE	DATE [YYMMDD-YYMMDD]	TIME [HHMM-HHMM]	AIRCRAFT TYPE	TAIL NUMBER	#
LUKE	ALL	ALL	ALL	ALL	ALL	1

FIGURE A-1. LISTING OF LUKE AFB MOAOPS LIBRARY OF MISSIONS AND FLIGHTS

TITLE: LUKE RUN OF ENTIRE LIBRARY

NO	MISSION NAME	MISSION DATE	SITE LOCATION	STARTING TIME HR MN SECS	FINISHING TIME HR MN SECS	A/C TYPE	A/C TAIL NO	SUPERSONIC TIME (SEC)	BOOM TIME (SEC)
1	5196-18	07/15/85	LUKE	15:28:58.99	15:30:40.59	F-15	7163	.0	.0
2	5196-18	07/15/85	LUKE	15:30:40.69	15:57:14.41	F-15	7163	16.0	.0
3	5196-18	07/15/85	LUKE	15:28:58.99	15:30:40.59		5049	.0	.0

```
**************************************************
***                                            ***
***     AIRCRAFT TYPE           NOT FOUND      ***
***               FLIGHT ABORTED               ***
***                                            ***
**************************************************
```

4	5196-18	07/15/85	LUKE	15:30:40.69	15:57:14.41	F-15	5049	11.0	.0
5	5196-18	07/15/85	LUKE	15:28:58.99	15:30:40.59	A-7	406	.0	.0

```
**************************************************
***                                            ***
***     AIRCRAFT TYPE A-7       NOT FOUND      ***
***               FLIGHT ABORTED               ***
***                                            ***
**************************************************
```

6	5196-18	07/15/85	LUKE	15:30:40.69	15:57:14.41	A-7	406	.0	.0

```
**************************************************
***                                            ***
***     AIRCRAFT TYPE A-7       NOT FOUND      ***
***               FLIGHT ABORTED               ***
***                                            ***
**************************************************
```

7	5196-18	07/15/85	LUKE	15:28:58.99	15:30:40.59	A-7	210	.0	.0

```
**************************************************
***                                            ***
***     AIRCRAFT TYPE A-7       NOT FOUND      ***
***               FLIGHT ABORTED               ***
***                                            ***
**************************************************
```

8	5196-18	07/15/85	LUKE	15:30:40.69	15:57:14.41	A-7	210	.0	.0

```
**************************************************
***                                            ***
***     AIRCRAFT TYPE A-7       NOT FOUND      ***
***               FLIGHT ABORTED               ***
***                                            ***
**************************************************
```

9	5203-15	07/22/85	LUKE	13:56:44.35	14:28:19.71	F-16	118	35.0	.0
10	5203-15	07/22/85	LUKE	13:56:44.35	14:28:19.71	F-16	126	135.0	87.0
11	5203-15	07/22/85	LUKE	13:56:44.35	14:28:19.71	F-4	6555	135.0	49.0
12	5203-15	07/22/85	LUKE	13:56:44.35	14:28:19.71	F-4	519	52.0	12.0
13	5203-15	07/22/85	LUKE	13:56:44.35	14:28:19.71	F-4	432	118.0	14.0
14	5203-15	07/22/85	LUKE	13:56:44.35	14:28:19.71	F-4	677	99.0	.0

FIGURE A-1. CONTINUED

17	5197-5-DACT	07/16/85	LUKE	08:54:02.47	09:33:19.57	F-16	126	109.0	.0
18	5197-5-DACT	07/16/85	LUKE	08:54:02.47	09:33:19.57	F-16	118	10.0	.0
19	5203-5-DACT	07/22/85	LUKE	08:59:27.93	08:27:27.93	F-15	5049	.0	.0
20	5203-5-DACT	07/22/85	LUKE	08:27:27.93	08:59:27.93	F-15	5--)	.0	.0
21	5203-5-DACT	07/22/85	LUKE	08:59:27.93	09:34:40.03	F-15	5049	.0	.0
22	5203-5-DACT	07/22/85	LUKE	08:59:27.93	08:27:27.93	F-16	126	.0	.0
23	5203-5-DACT	07/22/85	LUKE	08:27:27.93	08:59:27.93	F-16	1	.0	.0
24	5203-5-DACT	07/22/85	LUKE	08:59:27.93	09:34:40.03	F-16	126	26.0	.0
25	5203-5-DACT	07/22/85	LUKE	08:59:27.93	08:27:27.93	F-16	118	.0	.0
26	5203-5-DACT	07/22/85	LUKE	08:27:27.93	08:59:27.93	F-16	1	.0	.0
27	5203-5-DACT	07/22/85	LUKE	08:59:27.93	09:34:40.03	F-16	118	157.0	74.0
28	6063-11	03/04/86	LUKE	12:36:03.85	12:52:51.05	F-16	001	105.0	60.0
29	6063-11	03/04/86	LUKE	12:36:03.85	12:52:51.05	F-16	002	24.0	.0
30	6063-11	03/04/86	LUKE	12:36:03.85	12:52:51.05		01	.0	.0

```
**************************************************
***                                            ***
***     AIRCRAFT TYPE           NOT FOUND      ***
***              FLIGHT ABORTED                ***
***                                            ***
**************************************************
```

31	6063-11	03/04/86	LUKE	12:36:03.85	12:52:51.05		02	.0	.0

```
**************************************************
***                                            ***
***     AIRCRAFT TYPE           NOT FOUND      ***
***              FLIGHT ABORTED                ***
***                                            ***
**************************************************
```

32	6063-11	03/04/86	LUKE	12:36:03.85	12:52:51.05	F-14	03	32.0	12.0
33	6063-11	03/04/86	LUKE	12:36:03.85	12:52:51.05	F-14	04	43.0	33.0
34	6062-11	03/03/86	LUKE	11:50:14.53	12:23:12.93	F-16	330	.0	.0
35	6062-11	03/03/86	LUKE	11:50:14.53	12:23:12.93	F-16	311	119.0	.0
36	6062-11	03/03/86	LUKE	11:50:14.53	12:23:12.93		100	.0	.0

```
**************************************************
***                                            ***
***     AIRCRAFT TYPE           NOT FOUND      ***
***              FLIGHT ABORTED                ***
***                                            ***
**************************************************
```

37	6062-11	03/03/86	LUKE	11:50:14.53	12:23:12.93		113	.0	.0

```
**************************************************
***                                            ***
***     AIRCRAFT TYPE           NOT FOUND      ***
***              FLIGHT ABORTED                ***
***                                            ***
**************************************************
```

38	6063-4	03/04/86	LUKE	08:35:47.73	08:57:30.23	F-15	5067	14.0	.0
39	6063-4	03/04/86	LUKE	08:35:47.73	08:57:30.23	F-15	5049	23.0	.0
40	6063-4	03/04/86	LUKE	08:35:47.73	08:57:30.23	F-18	303	.0	.0
41	6063-4	03/04/86	LUKE	08:35:47.73	08:37:30.23	F-18	304	.0	.0
42	6062-8	03/03/86	LUKE	10:28:54.97	10:55:51.07	F-15	7164	2.0	.0
43	6062-8	03/03/86	LUKE	10:28:54.97	10:55:51.07	F-15	6102	.0	.0
44	6062-8	03/03/86	LUKE	10:28:54.97	10:55:51.07	F-18	302	.0	.0
45	6062-8	03/03/86	LUKE	10:28:54.97	10:55:51.07	F-18	300	8.0	.0

FIGURE A-1. CONTINUED

```
NUMBER OF BOOM PRODUCING SORTIES(FLIGHTS):   10

USING MACH NO CALCULATED FROM GROUNDVELOCITIES
    TOTAL SUPERSONIC TIME      =      1528 SECONDS
    TOTAL BOOM PRODUCING TIME =       393 SECONDS
USING TELEMETERED MACH NO CALCULATED FROM AIRSPEED
    TOTAL SUPERSONIC TIME      =      2955 SECONDS
    TOTAL BOOM PRODUCING TIME =       874 SECONDS
```

FIGURE A-1. CONTINUED

TITLE: LUKE RUN OF ENTIRE LIBRARY

X-COORD LOWER BOUND CELL 2 = -132000.0 CELL SIZE = 5280.000

. . . . 7 . . 32 21 22 30 31 22 19 11
5 9 14 15 18 32 18 23 18 16 15 5 5 5 . . . . . .
. . . .

Y-COORD LOWER BOUND CELL 2 = -132000.0 CELL SIZE = 5280.000

. . . . 1 4 2 2 5 5 4 6 9 11 25
28 36 25 20 20 26 19 20 22 [illegible] 12 5 7 14 9 9 3 6 4 4
4 5 4 . . . .

Z-COORD LOWER BOUND CELL 2 = [illegible].0 CELL SIZE = 1000.000

. . . . 28 53 21 6 18 12 9 22 20 13 10 8 15
4 37 29 23 12 5 . . . [illegible] 10 6 6 5 . . . . . .
. . . .

EFFECTIVE HEIGHT LOWER BOUND CELL 2 = .0 CELL SIZE = 1000.000 RMS =15617.202

. . . . . . 3 72 20 10 24 26 21 33 19 13 8 11 15 15
10 6 7 22 14 18 18 3 2 . 2 . 1 . . . .
. . . .

MACH NUMBER LOWER BOUND CELL 2 = .0 CELL SIZE = .020 RMS = 1.167

. . 5 14 36 32 57 39 41 42 40 18 11 5 7 5 7 10 6 3
3 4 6 2 . . . .
. . . .

CUTOFF MACH NO. LOWER BOUND CELL 2 = 1.0 CELL SIZE = .020 RMS = 1.073

. . 102 63 62 99 19 41 7 . . . .
. . . .
. . . .

EFFECTIVE MACH NO. LOWER BOUND CELL 2 = 1.0 CELL SIZE = .020 RMS = 1.296

. . 2 11 13 36 40 32 26 51 16 15 10 12 6 14 12 2 4 5
3 3 4 3 2 8 5 7 2 2 8 . 2 . 2 1 . 2 4 2
. 2 1 4 3 2 2 2 3 1 1 4 1 . . . . . .

OVERPRESSURE (PSI) LOWER BOUND CELL 2 = .0 CELL SIZE = .250

. . . . 10 37 29 36 27 16 20 13 16 2 13 9 11 17 5 4
8 7 9 13 20 20 9 6 6 . . . .
. . . .

PEAK LEVEL LOWER BOUND CELL 2 = 115.0 CELL SIZE = .500

. . . .
. . . . 4 4 5 9 13 12 8 10 9 10 19 10 9 10 16 6
10 9 9 10 8 13 26 11 7 8 15 10 5 7 8 13 15 33 12 10
. . . .

C-LEVEL LOWER BOUND CELL 2 = 90.0 CELL SIZE = .500

. . . .
. . 4 4 5 9 13 12 8 10 9 10 19 10 9 10 16 6 10 9
9 10 8 13 26 11 7 8 15 10 5 7 8 13 15 33 12 [illegible] . .
. . . .

A-LEVEL LOWER BOUND CELL 2 = 80.0 CELL SIZE = .500

. . . . 3 1 3 3
3 4 10 9 7 5 10 4 7 7 5 15 7 10 6 5 12 12 4 2
10 6 7 6 6 9 6 9 3 8 6 7 5 8 13 7 3 3 7 7
7 13 13 27 10 8 5 . . . .

TIME GREATER THAN MACH 1.0 (SEC) = 1528 TIME GREATER THAN CUTOFF MACH NO (SEC) = 393

FIGURE A-2. SUPERSONIC FLIGHT STATISTICS FOR LUKE AFB

```
X-COORD          LOWER BOUND CELL 2 = -137000.0    CELL SIZE = 5280.000

Y-COORD          LOWER BOUND CELL 2 = -132000.0    CELL SIZE = 5280.000

52  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
51  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
50  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
49  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
48  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
47  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
46  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
45  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
44  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
43  .  .  .  .  .  .  .  .  .  .  .  .  .  4  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
42  .  .  .  .  .  .  .  .  .  .  .  .  .  5  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
41  .  .  .  .  .  .  .  .  .  .  .  .  .  2  2  .  .  .  .  .  .  .  .  .  .  .  .  .  .
40  .  .  .  .  .  .  .  .  .  .  .  .  .  .  4  .  .  .  .  .  .  .  .  .  .  .  .  .  .
39  .  .  .  .  .  .  .  .  .  .  .  .  .  .  4  .  .  .  .  .  .  .  .  .  .  .  .  .  .
38  .  .  .  .  .  .  .  .  .  .  .  .  .  .  2  2  .  .  .  .  .  .  .  .  .  .  .  .  .
37  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  3  .  .  .  .  .  .  .  .  .  .  .  .  .
36  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  9  .  .  .  .  .  .  .  .  .  .  .  .  .
35  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  9  .  .  .  .  .  .  .  .  .  .  .  .  .
34  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  1  8  .  .  .  .  .  .  .  .  .  .  .  5
33  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  7  .  .  .  .  .  .  .  .  .  .  .  .
32  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  4  .  .  .  .  .  .  .  1  .  .  .  .
31  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  2  .  .  .  .  .  2  .  1  4  3  .  .
30  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  3  3  .  .  .  .  5  .  5  4  1  .
29  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  2  .  .  3  3  .  .  2  4  2  2  .  4  .
28  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  4  2  .  .  3  3  .  3  .  5  .  .  .  .
27  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  5  1  .  .  2  5  .  .  1  5  .  .  .
26  .  .  .  .  .  .  .  .  .  .  .  .  1  .  .  .  3 10  .  .  .  .  5  2  .  3  .  2  .
25  .  .  .  .  .  .  .  .  .  .  .  .  4  .  .  .  .  1  5  .  .  .  .  4  2  .  .  4  .
24  .  .  .  .  .  .  .  .  .  .  .  .  5  .  .  .  .  3  3  2  .  .  .  .  4  2  .  .  .
23  .  .  .  .  .  .  .  .  .  .  .  .  4  .  .  .  .  4  2  3  .  .  .  .  1  5  1  .  .
22  .  .  .  .  .  .  .  .  .  .  .  .  3  .  .  .  .  .  3  .  .  .  .  .  1  6  4  3  8
21  .  .  .  .  .  .  .  .  .  .  .  .  4  .  .  .  .  .  .  .  .  .  .  .  .  .  6  4  .
20  .  .  .  .  .  .  .  .  .  .  .  .  3  .  .  .  .  .  .  .  .  .  .  .  .  .  .  5  5
19  .  .  .  .  .  .  .  .  .  .  .  .  4  .  .  .  .  .  .  .  .  .  1  .  .  .  .  .  .
18  .  .  .  .  .  .  .  .  .  .  .  .  4  .  .  .  .  .  .  .  .  4  1  .  .  .  .  .  .
17  .  .  .  .  .  .  .  .  .  .  .  .  .  4  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
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```

FIGURE A-3, GEOGRAPHIC LOCATION OF SUPERSONIC FLIGHTS FOR LUKE AFB

X-COORD LOWER BOUND CELL 2 = -132000.0 CELL SIZE = 5280.000

Y-COORD LOWER BOUND CELL 2 = -132000.0 CELL SIZE = 5280.000

```
52  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
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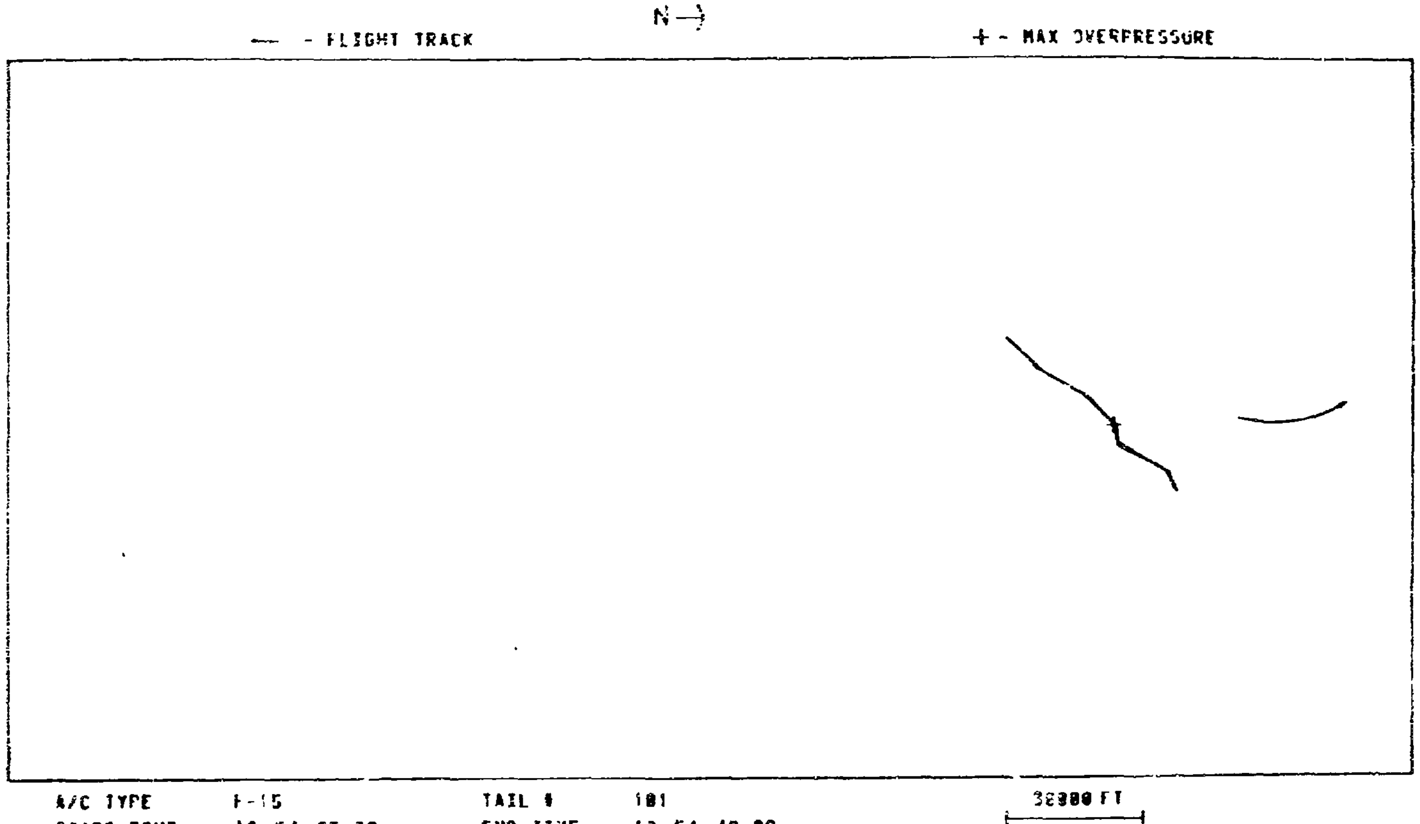
FIGURE A-3. CONTINUED



A/C TYPE	F-15	TAIL #	101
START TIME	12 54 25 39	END TIME	12 54 48 09
START ALT	22 54 K FEET	END ALT	20 16 K FEET
START MACH #	1 0182	END MACH #	1 0861
CARPET BOOM LEVEL	3 04 PSF	RANGE CENTER	
MAXIMUM OVERPRESSURE	9 29 PSF	LAT	33 48 0 N
ENHANCEMENT FACTOR	3 06	LONG	106 25 0 W

AREA OF 147 50 DB CONTOUR LEVEL 0 2570 SQ MILES
AREA OF 145 00 DB CONTOUR LEVEL 2 5600 SQ MILES
AREA OF 142 50 DB CONTOUR LEVEL 5 4464 SQ MILES

COORDINATES OF MAXIMUM OVERPRESSURE

X COORDINATE	53 69	K FEET
Y COORDINATE	-27 36	K FEET
ALTITUDE	4 50	K FEET

FLIGHT SEGMENT IDENTIFICATION

MISSION NAME	5282717-2061
MISSION DATE	10/09/85
MISSION SITE	HOLLOMAN

FIGURE A-4. SAMPLE SCRATCH PAD FOR A HOLLOMAN AFB FLIGHT

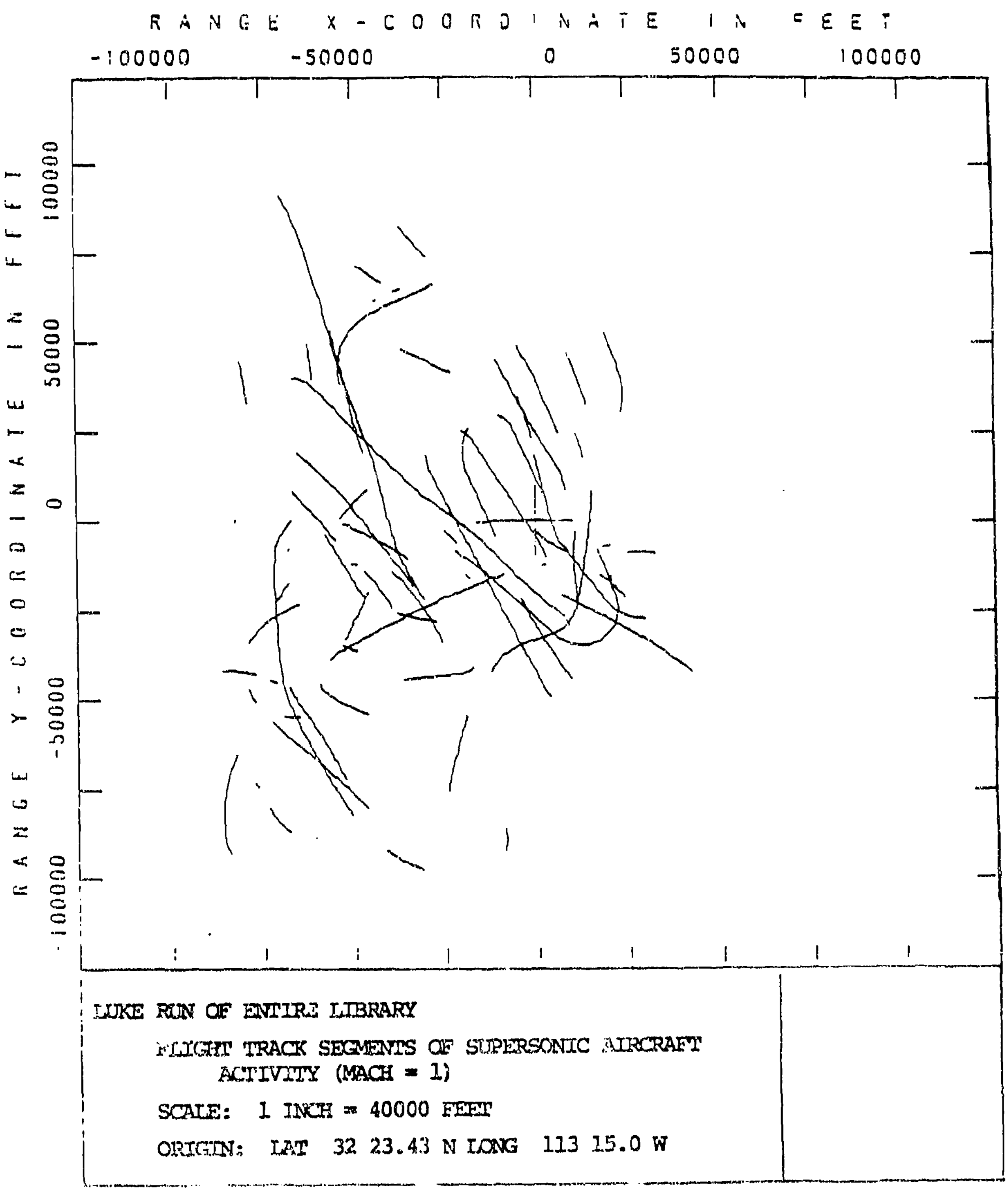


FIGURE A-5. SUPERSONIC AIRCRAFT FLIGHT TRACK MAP FOR LUKE AFB

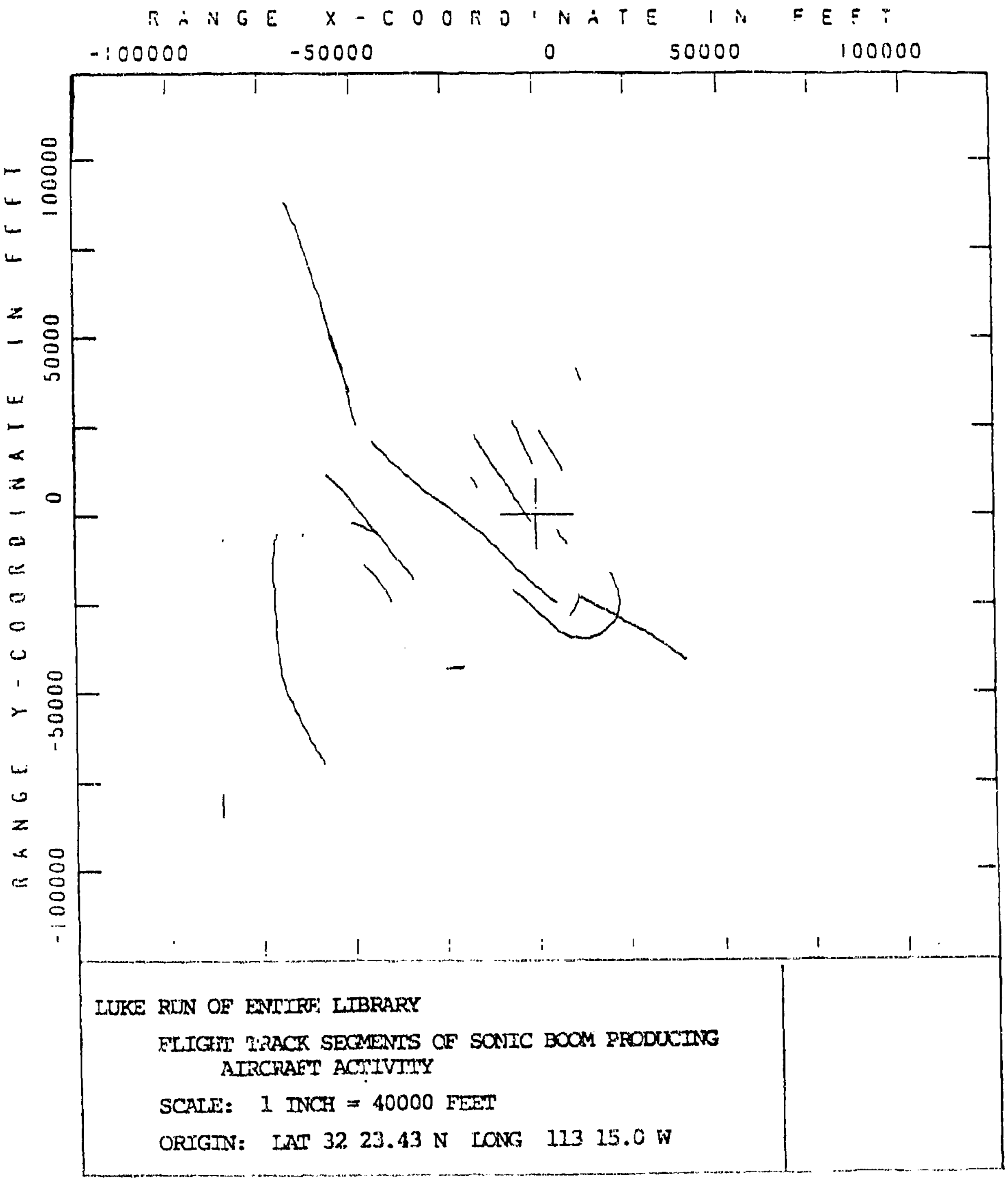
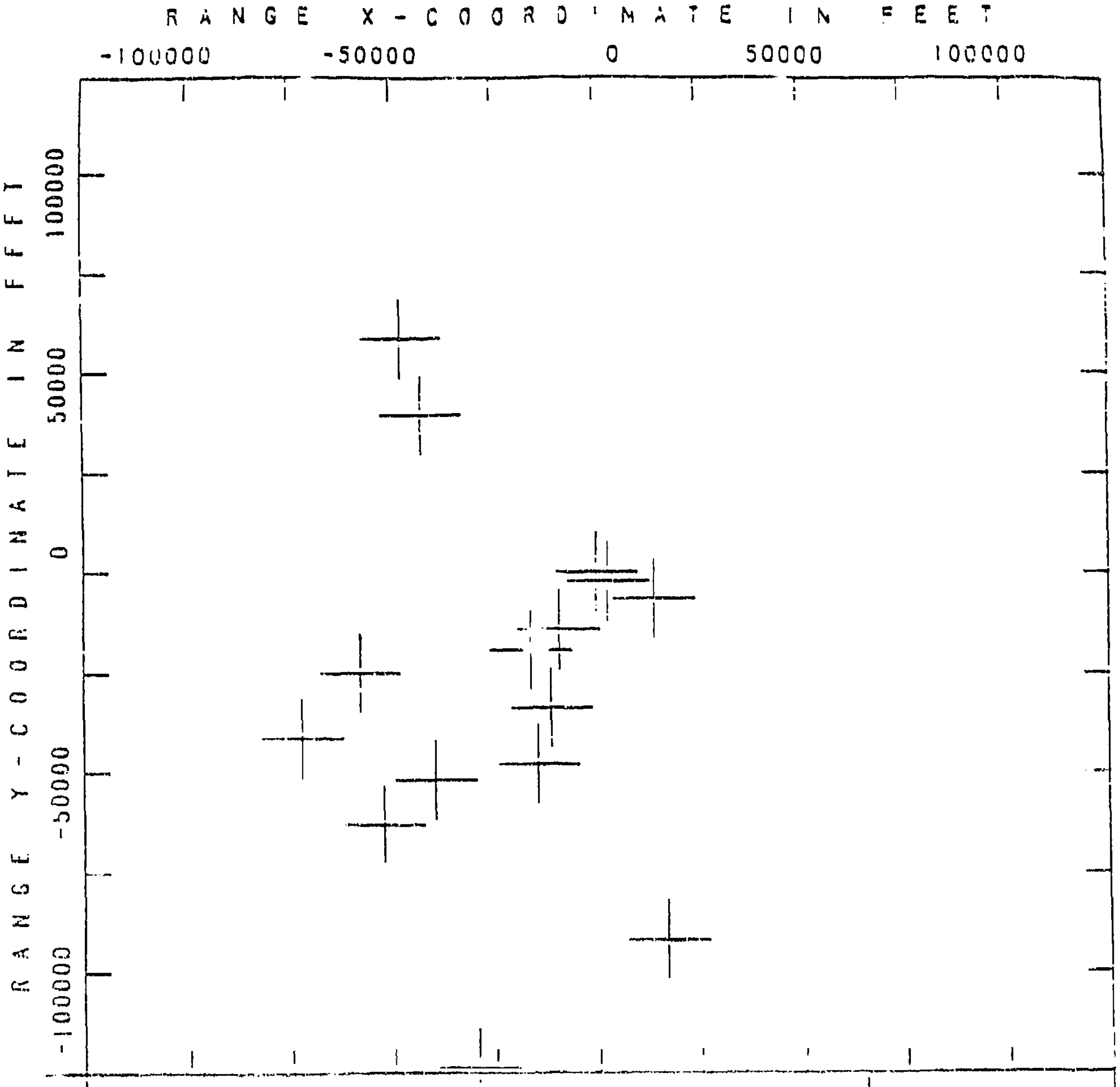


FIGURE A-6. FLIGHT TRACK MAP FOR SONIC BOOM PRODUCING FLIGHTS



LUKE RUN OF ENTIRE LIBRARY

LOCATION OF FOCUS BOOM MAXIMUM OVERPRESSURES

SCALE: 1 INCH = 40000 FEET

ORIGIN: LAT 32 23.43 N LONG 113 15.0 W

FIGURE A-7. LOCATION OF FOCUS SONIC BOOM MAXIMUM OVERPRESSURES

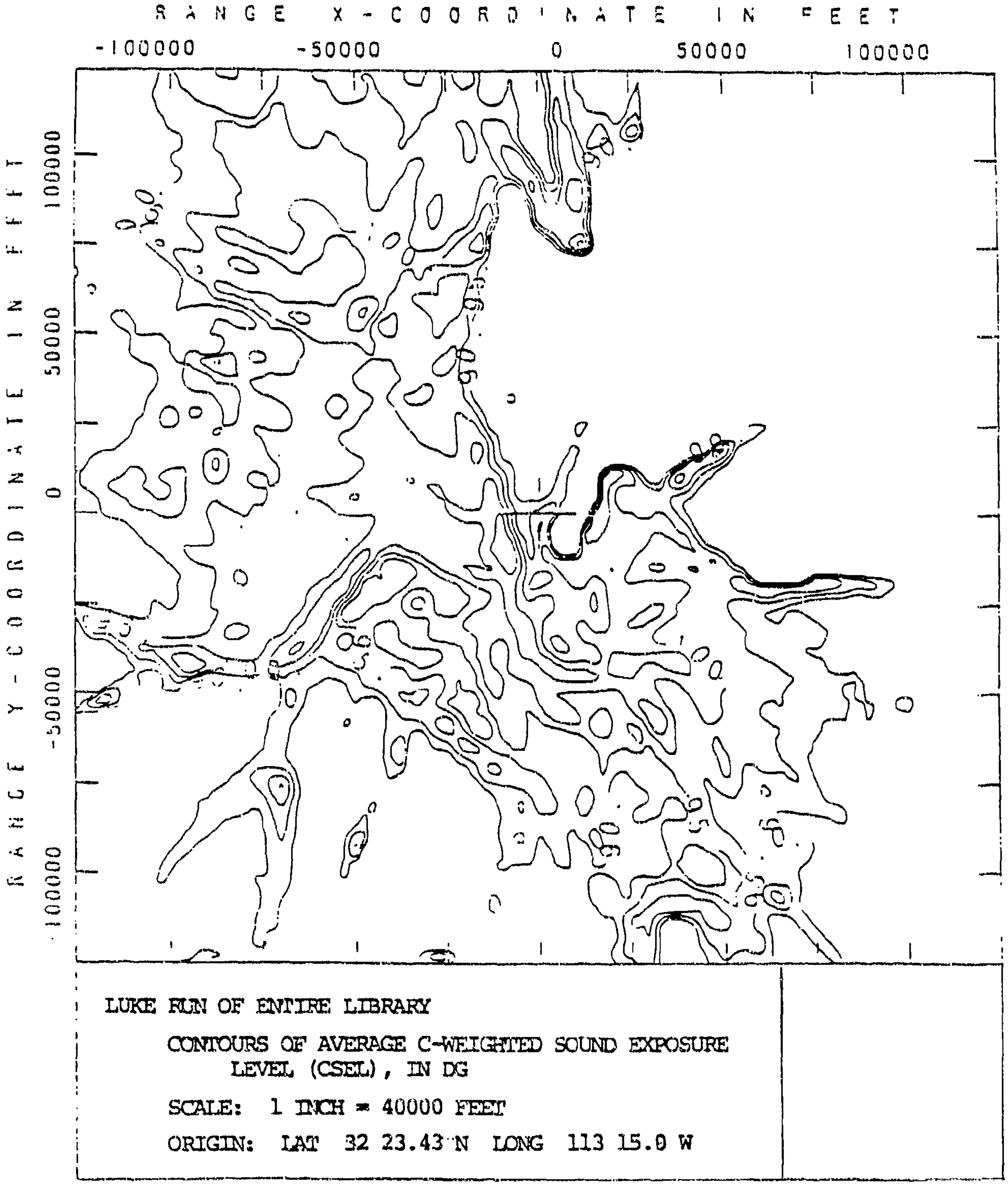


FIGURE A-8. AVERAGE C-WEIGHTED SOUND EXPOSURE LEVELS FOR LUKE AFB LIBRARY